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Changing mountain permafrost from the 1970s to today – comparing two examples from Niwot Ridge, Colorado Front Range, USA

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with 7 figures and 2 tables

Abstract. Melting mountain permafrost is reported from alpine areas around the world as a direct consequence of rising air temperatures over the past decades. However, alpine sites that offer sufficient older data to compare with recent conditions are rare. The study site Niwot Ridge, situated at ~3600 m a.s.l. in the Front Range of the Rocky Mountains, Colorado, USA, offers permafrost distribution data from the early 1970s. We used four different approaches to evaluate and compare the old data with recent conditions and to discuss consequences in how the old data should be considered.

(i) Air photographs and survey stakes were used to compare modern surface conditions of a solifluction lobe with those in the past. Despite high resolution of the air photographs (0.3 m), the error of position after geo-rectification was higher (± 1.0 m) than average displacement rates of gelifluction lobes (10 mm * a^{-1}), rendering this approach unsuitable. Replication of a 1963–1967 study of soil movement from 2006–2009 yielded average movement rates of 11.4 mm * a^{-1} compared to 9.4 mm * a^{-1} in the 1960s.

(ii) Temperature profiles of a three-year survey (2007–2009) to depths of 7 m were compared with data from the 1970s from the same site. Modern temperature profiles document a complex annual curve that includes several weeks of unfrozen conditions, this finding is in contrast with the permafrost conditions reported from the 1970s.

(iii) Electric resistivity profiles on a gelifluction lobe, surveyed in different seasons during the year, show the freezing front down to 2 m depth during the early winter, the melting process during spring conditions and the complete melt of all ice lenses during the summer months. Geophysical results corroborate data from nearby temperature loggers and were used to extend the survey to other areas on Niwot Ridge.

(iv) A simple 1 D-heat flow model was driven by the annual temperature variations of 1972 and 2008, resulting in several weeks of unfrozen conditions at various depths but with temperatures close to freezing during the 1970s.

Our study documents that at present, on south facing slopes, permafrost neither exists at 2 m depth on wet sites nor at 4 m depth on dry sites as suggested during the 1970s. Our modeling approach further suggests that, except on wet gelifluction lobes, it is likely that permafrost was not present at 3600 m during 1970, if so, permafrost degradation on south facing slopes on Niwot Ridge was not driven by recent climate change. However, north-facing slopes do cover permafrost, and certainly did in the 1970s, they are most probably affected by climate warming as already documented by a changing hydro-chemical signal in nearby streams.

Key words: Niwot Ridge USA, mountain permafrost, climate change, electric resistivity tomography, gelifluction

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1 *Introduction*

Globally rising temperatures affect permafrost in Arctic and Antarctic regions (Schuur & Abbott 2011) and its possible degradation is seen as a major challenge in the discussion of global change (Haeberli et al. 2011, Harris 2005, Lemke et al. 2007). Harris et al. (2003) also present clear evidence of rising air temperatures and warming permafrost for the European Mountains, and Li et al. (2008) reach similar conclusions for high altitude areas in China. As a consequence, extensive monitoring programs have been established to survey changes of subsurface temperatures in high mountain regions such as Switzerland (e.g., Noetzli & Vonder Mühll 2010).

Mountain permafrost in the USA is mainly located in Alaska, but there are also areas of frozen ground described in the Front Range of the Colorado Rocky Mountains above 3300 m a.s.l. (summarized in Janke 2005). Studies on the permafrost distribution and associated periglacial processes of the Front Range were started in the late 1960's and the early 1970's (Benedict 1966, 1970, Ives & Fahey 1971, see also Fig. 1).

Today, in the US the National Science Foundation (NSF) is funding two research projects, the Niwot Ridge Long Term Ecological Research Site (LTER webpage, n.d.) and the Boulder Creek Critical Zone Observatory (BC CZO webpage, n.d.), to study a high alpine area that was the focus of permafrost research in the 1960s and 1970s. Research includes studies of: (1) genesis, (2) evolution, and (3) physical and chemical parameters of the subsurface. Rock glaciers and active block fields also have been studied in many nearby areas and in the San Juan Mountains (e.g., Degenhardt 2009, Madole 1972, White 1971, 1976). The sites on Niwot Ridge provide an ideal chance to link data from more than 40 years ago with modern techniques of permafrost detection and monitoring and to discuss the results in the context of changing temperatures in the future.

Permafrost is defined on the basis of temperature as sediment or rock that remain below 0 °C throughout the year. It forms when the ground cools during the winter to produce a frozen zone that persists through two following summers (e.g., Williams & Smith 1989). Permafrost occurrence is classified as continuous, discontinuous, or sporadic, and an overview of its worldwide distribution is given by Smith & Riseborough (2002). Mountain permafrost composes only a small fraction of the worldwide permafrost distribution (Haeberli et al. 1993), but it is known from high altitude regions throughout the world, for example the Himalayas in Asia (Jin et al. 2000), the Alps in Europe (Harris et al. 2003), and the Rocky Mountains in North America (Janke 2005).

Solifluction can be defined as "*the slow flowing from higher to lower ground of masses of waste, saturated by water...*" (Andersson 1906). As this definition does not restrict the process to a periglacial environment more specific terms such as "*gelisolifluxion*" (Baulig 1956), "*gelifluction*" (Washburn 1967), and "*congelifluxion*" (Dylik 1967) have been introduced to describe solifluction movement over permanently or periodically frozen ground. We use the term gelifluction in this paper. Water availability and sufficient fine matrix (e.g., silts, clays, organic matter) are necessary preconditions so that winter frost penetration produces ice segregation lenses and frost heave (Harris et al. 2008), during summer thaw, infiltration of water is limited by the ice lenses at deeper parts of the subsurface, leading to an active water-saturated zone that moves downslope (e.g., Benedict 1970, Kinnard & Lewkowicz 2005, Smith 1988).

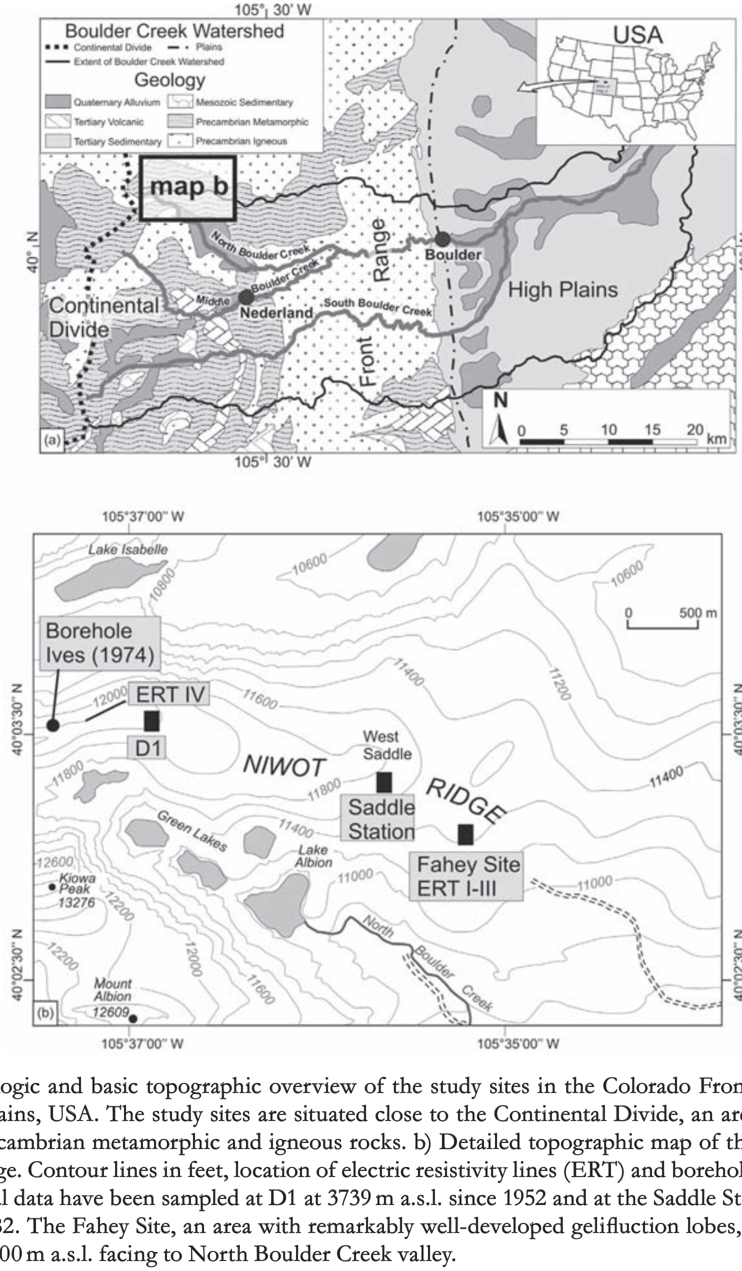

Fig. 1. a) Geologic and basic topographic overview of the study sites in the Colorado Front Range of the Rocky Mountains, USA. The study sites are situated close to the Continental Divide, an area that consists mainly of Precambrian metamorphic and igneous rocks. b) Detailed topographic map of the selected sites on Niwot Ridge. Contour lines in feet, location of electric resistivity lines (ERT) and boreholes as indicated. Meteorological data have been sampled at D1 at 3739 m a.s.l. since 1952 and at the Saddle Station at 3528 m a.s.l. since 1982. The Fahey Site, an area with remarkably well-developed gelifluction lobes, is located on a shoulder at 3500 m a.s.l. facing to North Boulder Creek valley.

Depth of freezing and thawing, transport distance over time, height of frost heave and resettlement, as well as areas of ice segregation on gelifluction lobes are directly linked to climatic conditions. However, intensities vary with respect to subsurface conditions such as perennial or seasonally frozen ground. On seasonally frozen ground, moving layers seem to be restricted to about

50 cm (Harris et al. 2008), as noted decades ago (Benedict 1970). As reported by Rudberg (1958) and Rapp (1967) active layer depths of 50 cm correspond with the thickness where the axes of elongate stones are oriented downslope. However, at sites with a permanently frozen subsurface, the depths and intensities of processes described above may differ considerably as documented in the field and the laboratory (Harris et al. 2008).

As the activity of these processes depends mainly on low air temperature and moisture, geomorphically active forms like gelifluction lobes will react to rising air temperatures. Leopold et al. (2010) documented the complete melt out of the ice within a gelifluction lobe on Niwot Ridge (named "Fahey Site") that had been thought to be underlain by permafrost for nearly 50 years. Recently Janke et al. (2012) obtained similar results in the nearby Rocky Mountains National Park, where they found evidence that permafrost distribution may have been overestimated or may have decreased due to rising temperatures over the last decades.

Leopold et al. (2008a, 2008b, 2010) reported data on the depth to bedrock and the shape of the critical zone in the vicinity of the Fahey Site and demonstrated that only seasonal ice lenses form at present, in the 1970s permafrost was documented at the site. In this paper we introduce new geophysical data from different times of the year to further evaluate our claim of seasonal ice-lenses and absence of permafrost. To compare old data from the late 1960s and early 1970s with more recent conditions, we used four different approaches: (i) measuring displacement rates of gelifluction lobes using air photographs, (ii) comparing temperature data of boreholes from 1970 and 2008, (iii) monitoring frozen ground in a 2 D manner using electric resistivity tomography (ERT)-techniques at several times during the year, and (iv) using a simple 1 D model driven by air temperature records from the 1970s and from 2008.

2 *Study site*

The Niwot Ridge area comprises a set of upland surfaces and adjoining slopes near the US-Continental Divide (W105° 36′ and N40° 03′) within the Colorado Front Range, which forms the eastern flank of the southern Rocky Mountains (Fig. 1). The range slopes from elevations over 4000 m a.s.l. down to the Colorado Piedmont and High Plains at about 1500 m a.s.l., 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 3740 m a.s.l. is –3.8 °C and mean annual precipitation is 993 mm (Barry 1973, Greenland & Losleben 2001, Williams et al. 1996, at site D1 in Fig. 1 and Table 1). There is a meteorological station located at the Saddle site (Fig. 1) at an elevation 3528 m a.s.l., 200 m from the Fahey study site. The climate record at the Saddle began in 1982, and, MAAT is warmer than at D1, –2.13 °C based on a temperature record from 1982–2011. Fig. 2 shows the trend of the annual sum of positive (+DD) and negative degree days (–DD) at D1 from 1960 to 2011.

We present data from the Fahey Site, located at 3500 m a.s.l., close to one of the meteorological stations (Saddle Station in Fig. 1). The site is named after the location of B. B. Fahey's doctoral-thesis studies (see also Ives & Fahey 1971). Less than 50 m below the Fahey Site, Benedict (1970) investigated in detail a similar but smaller lobe in his landmark study of periglacial processes (his site no. 45, Benedict 1970). The Fahey Site consists of a 50 m wide and 70 m long turf-banked

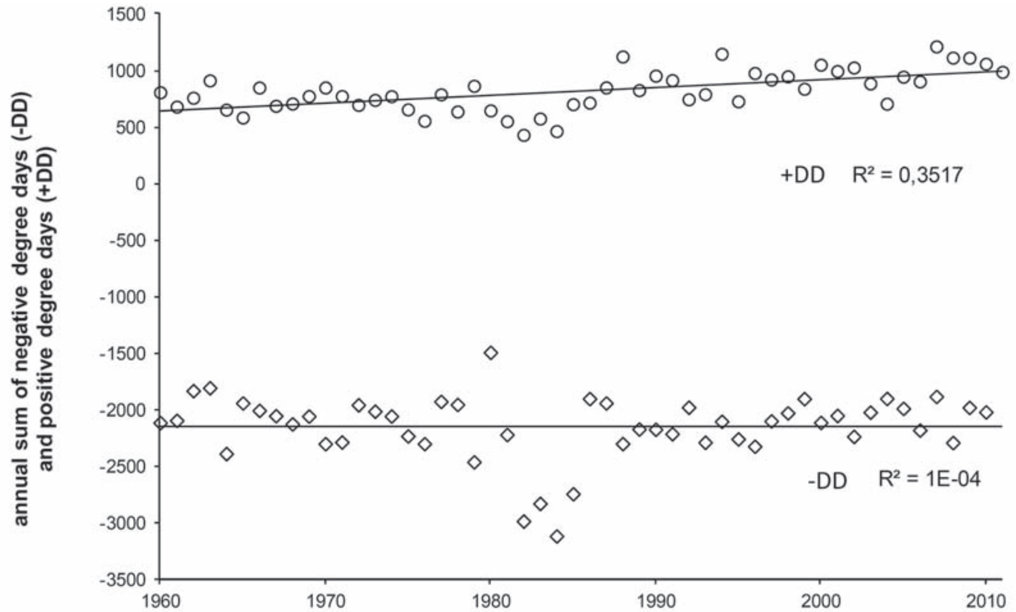

Fig. 2. Annual sum of negative- (–DD) and positive-degree days (+DD) based on mean daily air temperature at D-1 (3740 m elevation), Niwot Ridge, 1960–2011. Note the declining values (+DD) from 1965 to 1976 followed by a constant ascending trend with different slope until 2011. In contrast –DD show less variation except for a few years in the 1980s and, furthermore, indicate a week cooling trend.

Table 1. Mean annual air temperature (MAAT) and mean summer air temperatures (MSAT) from the D1 and the Saddle meteorological station calculated for various years. Saddle Station opened in 1982, however data from 1968 were provided by Ives & Fahey (1971).

D1 station

year	[MAAT °C]	[MSAT °C]	year	[MAAT °C]	[MSAT °C]
1968	–3.76	5.56	2007	–1.55	9.37
1969	–3.25	6.19	2008	–2.97	8.54
1970	–3.72	6.69	2009	–2.32	8.21
1971	–3.94	5.86	2010	–2.34	8.63
1972	–3.24	5.64	2011	–3.00	8.5
average	**–3.58**	**5.99**		**–2.44**	**8.65**

Saddle meteorological station

year	[MAAT °C]	[MSAT °C]	year	[MAAT °C]	[MSAT °C]
1968	–0.8	–	2007	–1.17	8.45
1969	–	–	2008	–2.52	7.33
1970	–	–	2009	–2.74	6.16
1971	–	–	2010	–2.44	7.51
1972	–	–	2011	–2.50	7.50
average	**–**	**–**		**–2.27**	**7.39**

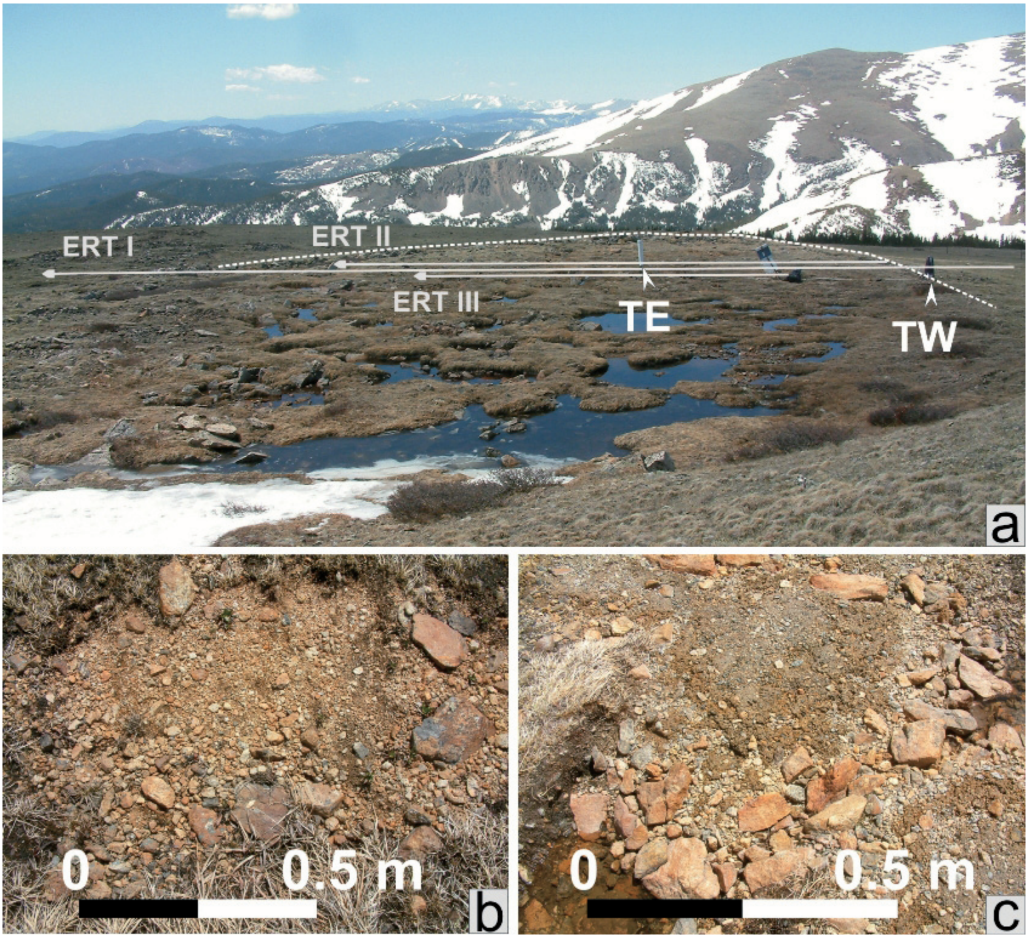

Fig. 3. a) Photographic overview of the Fahey Site in May 2010: view is towards the south. The local slope steepens toward North Boulder Creek valley about 100 m south of the lobe. Indicated are the outer boundary of the lobe (white dotted line), the location of the electric resistivity lines (ERT I-III) and the location of the two boreholes equipped with temperature loggers (TE = Thermistor East and TW = Thermistor West). Note the ponds on the lobe, indicating an underlying impermeable subsurface, which results in a high water table. b) and c) Examples during May 2010 of patterned ground, which is restricted to the wet parts near the ponds and snow cover in a). Larger stones seem not to be very active but inner parts of circles frequently show small mudboils.

gelifluction lobe with local patterned ground and ponds that are persistent during the thaw period (Fig. 3a). The patterned ground includes fresh mud boils which appear in the center of stone rings during the early thawing period: larger stones and boulders seem to stay in place (see Fig. 3b and c). Two cased boreholes with temperature loggers at different depths down to 7 m were installed in 2007 (TE and TW in Fig. 3a).

3 *Methods*

3.1 *Air photography and survey stakes*

Air photographs of different ages have been successfully applied to different areas in the past to describe displacement rates in periglacial landscapes. This technique worked especially well for fast moving periglacial forms such as some rock glaciers (e.g., Roer & Nyenhuis 2007). We used air photography (provided by the Niwot LTER program) from 1946, 2003 and 2008 with a resolution of 0.3 m in order to describe gelifluction displacement rates. Additionally, we used unpublished soil movement data, collected during the years 2006–2009, on lobe no. 45. The study replicates methods and design as described by Benedict (1970), and consists of measuring movement distances of buried stakes along the surface related to a base line.

3.2 *Subsurface temperatures*

Subsurface temperatures were measured at two boreholes on and beside the gelifluction lobe by several loggers at depths of 0.05, 0.2, 0.4, 0.8, 1.2, 2,0 and 2.6 m at the East logger (TE in Fig. 3a) and of 0.05, 0.2, 0.4, 0.8, 1.2, 2.0, 2.85, 5.0 and 7.0 m at the West logger (TW in Fig. 3a). Thermisters were calibrated using a two-point calibration at 0 °C and –22 °C. Temperatures were collected every 10 minutes and averaged to hourly and daily values between 2007 and 2009. Here we introduce a nearly complete dataset from the year 2008.

Older data from the 1970s were taken from: (1) Ives (1973, 1974) who provided subsurface temperature data for 1971–1973 from a borehole near D1, (2) from Ives & Fahey (1971) for the gelifluction lobe, as well as from (3) Benedict (1970). Data were generated from published graphs, lowering precision. Due to the manual reading of analog devices in those days, the density of measurements is lower, approximately 2–3 readings per month for subsurface data from the 1970s (Ives 1974).

Climatic data on the daily mean air temperature were taken from the Niwot Ridge LTER webpage (n.d.) for the D1 and for the Saddle meteorological stations.

3.3 *Electric Resistivity Tomography (ERT)*

A multi electrode system 4punktlight hp from Lippmann Geophysikalische Messgeräte (100 electrodes) was used to collect two-dimensional DC resistivity tomography profiles (Lippmann 2008) on the gelifluction lobe at 3500 m a.s.l. and on a north-facing slope close to the D1 site at 3740 m a.s.l. (Fig. 1 and Fig. 3a). Profiles were measured during different seasons of the year to observe different freezing and melting conditions on the gelifluction lobe. Contact resistances were noted between 2–3.5 kΩm during the winter conditions in December 2009 whereas in the spring and summer/fall conditions values ranged between 0.15–0.6 kΩm, which accounts for good coupling of the electrodes to the ground especially during the non-freezing period. We used a Wenner array with a spacing of 0.25 m (ERT III) for detailed surface surveys and 0.5 and 1 m spacing (ERT II and ERT I) to achieve deeper penetration. The array normally allows higher current with resulting higher potentials and an according low signal-noise ratio compared to other arrays. Depending on the line length this generally resulted in observation depths between 1.5 and 18 m with a resolution of ± 0.1 to 0.5 m.

For the Wenner array, the equation relating the measured current (I), voltage drop (ΔV) and apparent resistivity (pa) is according to TELFORD et al. (1990):

$$pa = 2\pi a * \frac{\Delta V}{I} \tag{1}$$

where (a) is the spacing between electrodes.

We measured with a frequency of 5 Hz and 0.1–10 mA. Resistivity between each point was measured 5 times with a maximum 3 % difference between the measurements. The apparent resistivity was noted online and inverted towards specific resistivity using the software RES2DINV 3.58 (LOKE & BARKER 1995). Least-squares inversion technique were used to compile specific resistivity models. After 5 iterations, models generally reached the desired convergence limit of 3.0 %. Models started with a damping factor of $\lambda 0 = 0.17$ and ended with $\lambda min = 0.05$. Models yielded RMS errors of 2.8 % to 19.2 % between the measured and the calculated apparent resistivity distribution. For each line we calculated the depth of investigation index (DOI) following OLDENBURG & LI (1999) in order to determine which areas of the model are sensitive to the measured physical properties. Reference models were calculated with resistivities of 0.1 and 10 times background resistivity, resulting in a two-sided difference (OLDENBURG & LI 1999). We developed scaled DOI values using models with 3 times depth of the estimated maximum depth of investigation with a vertical-horizontal damping factor relationship of 1:1. Results were normalized to 1 and the threshold value, used to determine areas below which the data are no longer sensitive to the physical properties of the subsurface, was set to 0.2 following HILBICH et al. (2009).

3.4 *1 D modeling of heat flow*

The heat equation describes how temperature changes through a heated or cooled medium over time and space (HILLEL 2004). The equation for heat flow under transient conditions (CARSLAW & JAEGER 1959, LUNARDINI 1981, WILLIAMS & SMITH 1989) is:

$$C\frac{\vartheta T}{\vartheta t} = k\frac{\vartheta^2 T}{\vartheta z^2} \tag{2}$$

with C representing the volumetric heat capacity [Jm^{-3}], T the mean annual temperature [°C], *t* the time [s], *z* the depth [m], and k the thermal conductivity. We used a very simple 1 D-model with finite differences programmed in Microsoft Excel® to solve the heat-flow equation in order to estimate temperature variations during the year at certain depths. Initial conditions were set to 0 °C. Upper boundary conditions were driven by the mean daily temperatures and lower boundaries were set to 0 °C at 2.2 and 4 m depth, respectively. We further used the 1 D model provided by NOETZLI & GRUBER (n.d.) to model sinusoidal analytical solutions for a 1-dimensional temperature profile in bedrock. Thermal diffusivity was set to 0.85 mm^2s^{-1} for the soil on the lobe and to 1.6 mm^2s^{-1} for the bedrock site (HILLEL 2004, MONOTEITH & UNSWORTH 1990, WITTINGTON et al. 2009).

4 *Results and interpretation*

4.1 *Measuring displacement rates of gelifluction lobes using air photographs and survey stakes*

Increased or decreased displacement rates of gelifluction lobes could indicate changes of the freeze and thaw processes of an area and our aim was to calculate displacement rates by comparing air photographs of different age in combination with soil movement data in the field. BENEDICT (1970) describes average displacement rates of 9.4 mm * a^{-1} between 1963 and 1967 on his lobe 45. The earliest available air photograph from 1946 gives a total maximum time span of observation of 60 years resulting in a total displacement of 56 cm if the rates of BENEDICT (1970) are extrapolated. On air photographs from 1946 compared to 2003/2008 (0.3 m resolution), the displacement of the gelifluction lobe unfortunately is close to the detection limit. Additionally, the geo-rectification of the various photographs using ARCGIS resulted in even higher uncertainties of over ± 1.0 m. The approach using air photographs yielded a negative result. A replication of the soil movement study from 1963–1967 resulted in an average movement rate of 11.4 mm * a^{-1} for the period of 2006–2009 which is only slightly faster than the 9.4 mm * a^{-1} from the 1960s (Table 2). It is consistent with rates from other forms such as coarse-stone banked terraces, which have even smaller displacement rates (~ 10 mm * a^{-1}, CAINE 1986).

Table 2. Soil movement rates on lobe 45 for the years 2006 to 2009 based upon 10 survey sticks equally distributed over the lobe. Indicated are results of individual years and a total average in mm.

Stake no	Distance [mm] 13-July-2006	Distance [mm] 20-July-2007	Movement [mm] 2006–2007	Distance [mm] 20-July-2008	Movement [mm] 2007–2008	Distance [mm] 13-July-2009	Movement [mm] 2008–2009
1	54.0	57.0	3.0	57.0	0.0	57.5	0.5
2	77.5	81.0	3.5	86.0	5.0	89.0	3.0
3	55.0	66.5	12.5	73.0	6.5	82.0	9.0
4	67.0	91.0	24.0	115.0	24.0	134.0	19.0
5	74.5	108.5	34.0	126.0	17.5	160.5	34.5
6	32.5	60.5	28.0	–	–	–	–
7	64.0	86.0	22.0	100.0	14.0	119.5	19.5
8	86.0	95.0	9.0	107.0	12.0	114.0	7.0
9	66.0	70.0	4.0	74.0	4.0	77.0	3.0
10	76.0	76.5	0.5	79.5	3.0	80.0	0.5
Movement sum			**14.0**		**9.6**		**10.07**
Movement average 2006_2009		**11.4 mm**					

4.2 *Comparing borehole data form 1970 and 2008*

Data from various years and sites on Niwot Ridge (Fig. 1) for subsurface temperatures below a depth of 1 m are sparse. Curves from 2008 show wide temperature variations at the surface for the eastern thermistor from –21 °C to +15 °C on the lobe and from –15 °C to +14 °C at the western thermistor beside the lobe (Fig. 3a). At both boreholes the amplitude between minimum and maximum temperatures throughout the year decreases remarkably at around 2 m depth and reaches its minimum near 3 m depth. Benedict (1970) described a minimum-temperature record from the fall and winter period of 1964–1965 down to 1.5 m. That curve seems to be similar to the data from TW, which is somewhat surprising because TW samples the drier site beside the lobe. At 1.3 m depth the curve from 1964–1965 reaches about the same minimum temperature as TE at this depth. Benedict (1970) did not measure data for the summer and for deeper depths, which makes a comparison of the curves from 1964–1965 with those from 2008 difficult. However, the curves clearly document that minimum temperature data from 1964–1965 and 2008 are similar to a depth of 1.2 m. Ives & Fahey (1971) report that a thermistor remained fractionally below 0 °C throughout the summer for the next three years (1968–1970) below 1.83 m, indicating permafrost. In contrast, both thermistors recorded temperatures above freezing at 2 m depth during 2008, indicating no permafrost.

TW offers records down to 5 and 7 m depth, where temperatures remained above 0 °C throughout the year (not visible in Fig. 4). This partly corresponds with notes from Ives (1974),

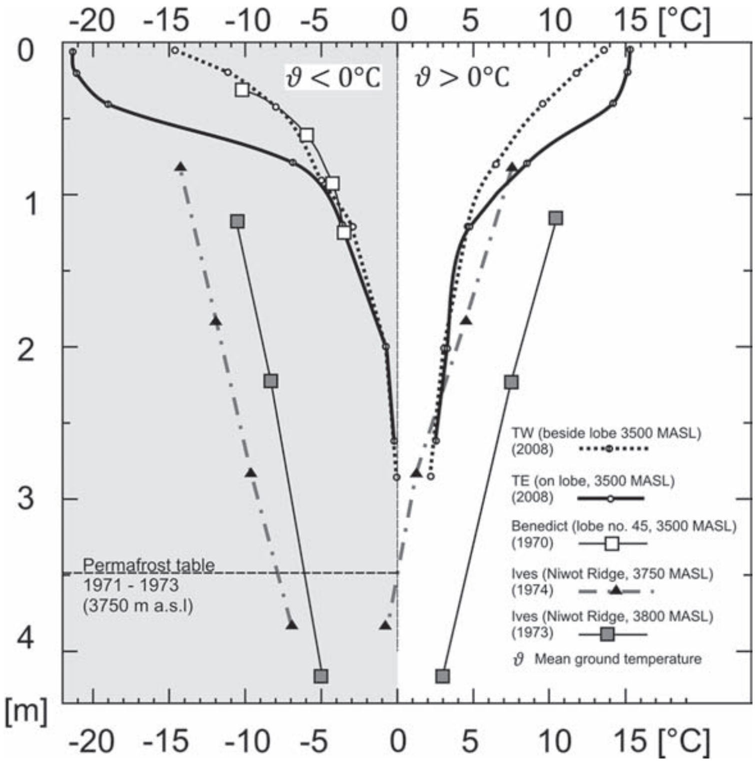

Fig. 4. Annual variations of the minimum and maximum subsurface temperatures at various depth from different years and sites at Niwot Ridge. Shaded side symbolizes temperatures below 0 °C. Note the similarity of the curve given by Benedict (1970) and the data measured in 2008. Recent data do not suggest permafrost conditions at 3500 m a.s.l., but data provided by Ives (1974) depict a permafrost table at 3.5 m depth on a north facing slope.

who reported that a thermistor at 4.5 m depth beside the lobe did not register freezing temperatures in October, but showed temperatures below freezing by mid December 1969.

A different graph published by Ives (1974) showed a thermistor record from a north facing site at 3750 m a.s.l. on Niwot Ridge. The site was about 700 m west of the D1 station, where the Ridge narrows to a crest with large blocks and bedrock outcrops (Jack Ives, personal communication 2010). Here we find much wider temperature amplitudes at greater depth compared to the curves from the lobe, and temperatures indicate a permafrost table at a depth of 3.5 m in 1972. The linear course of the temperature curve reflects the simple subsurface bedrock geology with a higher thermal diffusivity of 1.6 mm^2s^{-1}, in contrast to the more complex mineral-organics-water-gas regimes with lower thermal diffusivity of 0.85 mm^2s^{-1}, consistent with higher variation in the thermal regimes near the surface and less in the deeper parts.

4.3 *Monitoring frozen ground in a 2 D manner using ERT techniques at several times during the year*

Initial geophysical measurements were made in 2005 using ground penetrating radar (GPR) to study the critical zone at various sites on Niwot Ridge including the Fahey Site (Leopold et al. 2008a, 2008b). These studies gave first indications of a seasonal frozen subsurface with no permafrost. Additional studies using ERT were performed in 2008–2009 (Leopold et al. 2010). Here we present a picture of the specific electric-resistivity values in the subsurface of the lobe during summer, winter, and spring in 2009–2010 (Fig. 5a–c, see Fig. 3 for location).

ERT I runs from a drier area west of the lobe, crosses the lobe and finishes on drier zones in the east. The central part between 25 m and ~ 60 m on the line represents the lobe. At both ends specific resistivity values > 0.8 kΩm were observed, reaching maximum values of > 3.0 kΩm. These less conductive zones are several meters thick down to about 12 m in the east. At 60 m and especially well-developed at 78 m, a v-shaped high resistivity zone is visible down to about 5 m, which corresponds well with the location of frost cracks filled with larger boulders and with only a few fines in between. Large lichens on the boulders as well as the undisturbed grass cover at the edges of these areas suggest inactivity at present. The subsurface of the lobe is basically characterized by low resistivity values (between 50 and 200 Ωm) indicating mostly water saturated weathered material down to more than 15 m. This subsurface stratigraphy is corroborated by drill holes down to 14 m (Leopold et al. 2008a) and a seismic refraction survey (Leopold et al. 2008b). At 20 m on the line and at 7–8 m depth the specific resistivity values slightly rise to > 0.3 kΩm, probably indicating a large boulder. This would corroborate drilling results from 2007 where a large boulder was hit at 7.2 close to the ERT line (Leopold at al. 2008a). ERT surveys during seven subsequent summers between 2006 and 2011 did not indicate an ice layer or ice lenses that one would expect if permafrost exists. Besides some minor parts on the beginning and the end of the line, depth of investigation (DOI) values of 0.1 and lower indicate that the inversion process is driven by the measured apparent resistivity values (e.g., Oldenburg & Li 1999), which is a good proof of quality check.

ERT II is on the same line as ERT I but is shorter as electrode distance was narrow: 0.5 m. It was measured during harsh winter conditions with air temperature at –24.5 °C on December 3rd

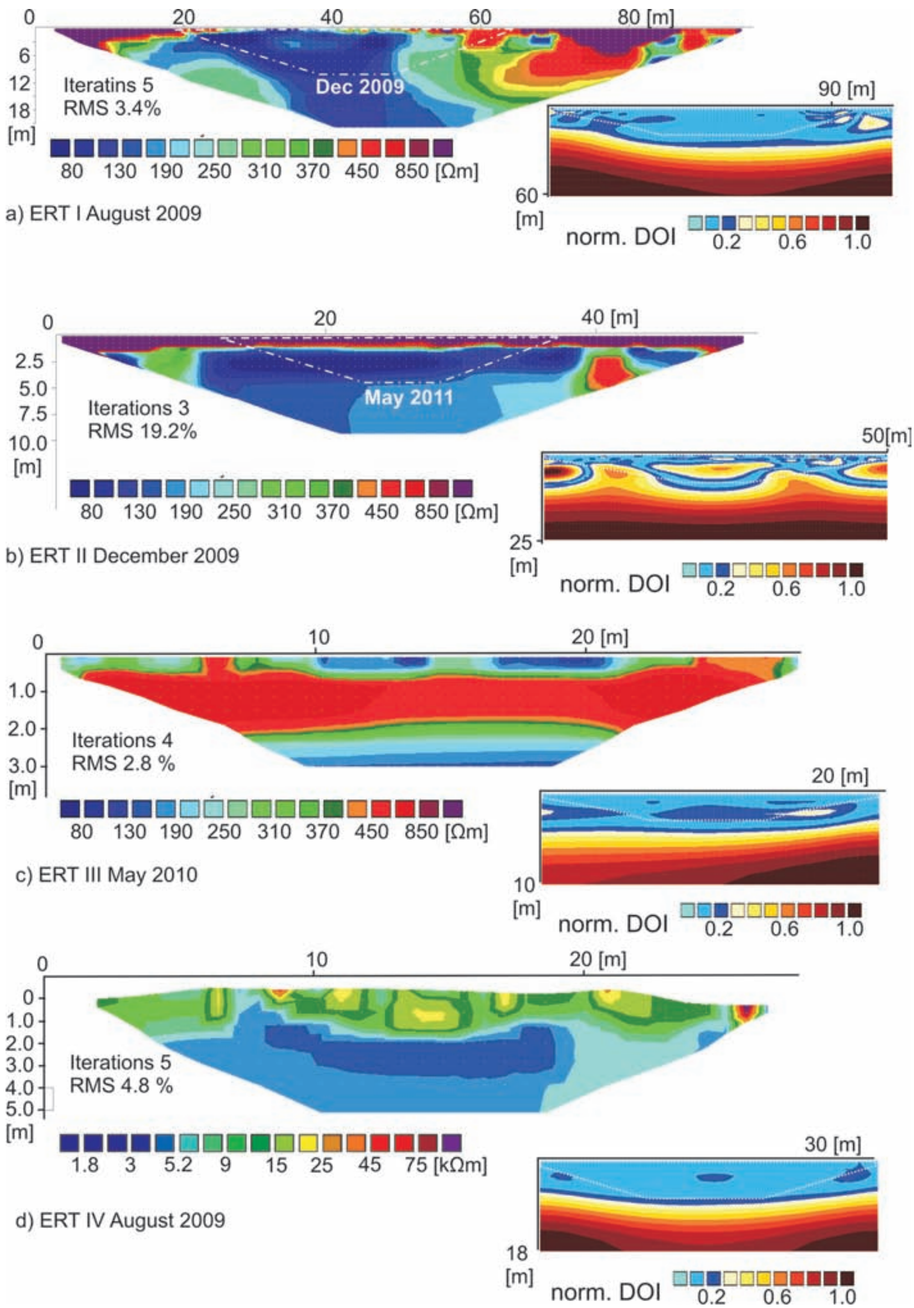

Fig. 5. Electric resistivity tomograms of two sites on Niwot Ridge. ERT I-III represent the same place but with varying lengths and depths and during different times of the year at 3500 m a.s.l. as indicated by the white dotted lines. ERT IV is at a different site at 3750 m a.s.l. on a north facing slope. Depth of investigation (DOI) values are given for all lines. White lines in DOI images indicate area of measured data. DOI values above 0.2 indicate areas where the inversion model is not sensitive for measured field data. Note the different value scale for ERT IV despite a similar color palette.

2009. Average daily temperature was –6.4 °C in November 2009. The specific resistivity values differ from the summer conditions insofar as a well-developed, 1.0–1.1 m thick low conductivity layer was observed close to the surface across the whole lobe. Values reach a maximum of 10 kΩm but average around 3 kΩm, we interpret the layer as the refreezing zone from the top during winter conditions. The steep gradient of the resistivity values at the lower boundary from 3 kΩm to less than 0.25 kΩm is interpreted as the depth of the freezing front during the survey in December 2009. TW recorded –1.5 °C at 0.8 m depth and +0.5 °C at 1.2 m depth, whereas TE recorded –2.63 °C at 0.8 m depth and –0.005 °C at 1.2 m depth, which corroborates the ERT interpretation. Beside two high resistivity spots at the beginning and at 40 m on the line, the subsurface below 1.2 m is characterized by low values of 0.05–0.25 kΩm. We interpret the low resistivity areas as the unfrozen wet zone of the lobe that was still storing summer heat. However, the DOI-values in the lower part of this measurement are partly above 0.2, which limits the interpretation of the inversion (Hilbich et al. 2009). In general, the model shows some weaknesses that are also expressed by a higher RMS value of 19.2 %. In permafrost studies interpretation of the inversion under high resistivity layers is somewhat tentative but ERT results and temperature data are consistent. ERT-III portrays the conditions during the following spring period in May 2010. The image shows a well-developed upper zone with resistivity values of 0.1–0.3 kΩm, which is separated from an underlying layer with higher values up to 1 kΩm. The gradient of the values between the two layers is very steep. It is interpreted as a melted layer lying above a still frozen zone on the lobe. The transition between those layers is at around 0.5 m. However, the thawed surface layer displays some horizontal variation, which represents patterned ground with water-saturated, fine-textured inner parts and coarser outer parts in a cross-sectional view. The resistivity values of the frozen part indicate that only interstitial ice lenses have formed, as pure ice would cause much higher values (e.g., Hauck & Kneisl 2008). Benedict (1970) and Ives & Fahey (1971) report small ice lenses within a soil matrix at various depths on the lobe 45, which is consistent with our ERT results. At a depth of about 2 m there is another steep gradient of resistivity values towards a zone with lower resistivity values of 0.1–0.3 kΩm. This zone represents the lower boundary of the freezing front of winter 2009/10, which confirms the results from the temperature records during the years 2007–2009. DOI-values below 0.2 indicate an inversion basically driven by the input data.

Our results demonstrate that ERT records the impacts of temperature changes at the point of water-phase change, which is known from other studies but documented here, for Niwot Ridge for the first time. Due to this positive result we measured another line in the vicinity of the borehole presented in Ives (1974), which was drilled in 1971. ERT IV is the result of this measurement, made on a flat and vegetated bench on the north slope of Niwot Ridge west of D1 (Fig. 5d, for location see Fig. 1b). The line starts at the top with a high resistivity layer of about 2 m in thickness. Values range between 10 and 15 kΩm in most places, but there are also spots with much higher values over 50 kΩm. The whole line is, therefore, separated by these high resistivity points, which we interpret as coarse stones and blocks of polygons of patterned ground, which are inactive at present. The lower values indicate the former margins of the polygons, which are filled with finer material covered by some vegetation today. At about 2 m depth resistivity values change across a steep gradient to lower values of about 3–5 kΩm. This zone is interpreted as solid bedrock. So far we have not measured higher electric resistivity caused by ice during summer conditions at various spots on Niwot Ridge. The most likely places would be areas with high water tables that are snow-free during December and January winter storms but accumulate snow in the spring, which protects against early summer solar radiation as noted previously by Ives (1973).

4.4 *Heat flow modeling*

In order to better validate the older data with the measured records from 2008 we used a simple one layer 1 D model to solve the equation for heat flow under transient conditions. The model did not include phase shift from water to ice and vice versa and was run mainly to decide if it is possible to form permafrost at 2 m depth in our study area using the air temperatures from the 1970s and from 2008. Model output was compared to measured values from 2008 at TE (Fig. 6).

Despite the model simplicity, measured and modeled data were surprisingly consistent for the first seven months. From January to August 2008, both modeled and measured results show that the temperatures at 2 m depth are nearly sinusoidal in form. However, starting in August there is a steep increase of the measured soil temperature from just below 0 °C to over 3 °C until October. Such a sharp rise in subsurface temperature can be best explained by an additional heat source. The site faces south and, therefore, it is strongly influenced by solar radiation as the sun zenith angle changes. By August solar energy effectively warms any water that flows through the slopes and into the lobe and directly influences the temperature at 2 m depth. As soon as all the ice has melted, no additional energy is needed for the phase shift, which leads to the steep rise of temperature at 2 m depth, despite the fact that air temperatures do not follow such a rise. This steep temperature rise from 0 °C to higher values was also recorded during the summers of 2007 and 2008, though at more shallow depths and, accordingly, earlier in the year. Our model cannot resolve such a phase shift since it is driven only by heat conduction. The modeled results portray the influence of lower air temperatures on the subsurface temperature at 2 m depth during the 1970s. The modeled curve

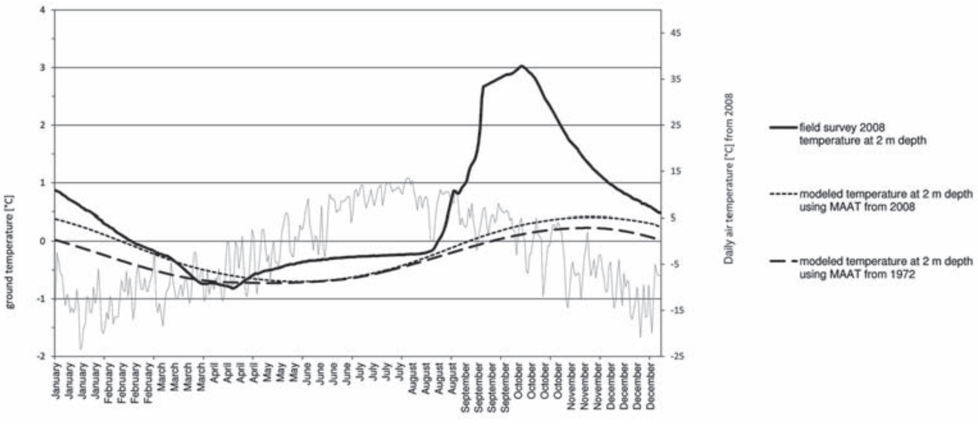

Fig. 6. Annual smoothed daily temperature record at 2.2 m depth measured on the gelifluction lobe in 2008 (continuous black line) compared to results derived from a 1 D model for heat flow under transient conditions. Model was driven by a change in mean annual air temperatures (MAAT) from 2008 (dashed black line) and 1972 (dotted black line). The gray temperature line gives mean daily air temperatures from 2008. Modeled data show a sinusoidal pattern whereas measured data indicate a steep rise in temperature by mid August when the ice melts out at this depth.

for 1972 is constantly below the curve of 2008. At a depth of 2 m the highest temperatures modeled for 1972 is 0.22 °C whereas for 2008 it is 0.41 °C. Summer air temperatures have risen over 2 °C since 1970 on the D1 station whereas winter temperatures seem to show no warming. The annual sum of positive degree-days (+DD) based on mean daily air temperature at D1 also shows a clear trend from 1960 to 2011 towards higher values ($R^2 = 0.35$, Fig. 2). Indeed, between 1968 and 1972, when BENEDICT (1970), IVES & FAHEY (1971) and IVES (1973, 1974) made their observations, a declining trend towards lower values is observable. In contrast, negative degree days (–DD), beside an anomaly in the early 1980s, do not show a warming trend but a week cooling trend. Taking the above model outputs and the climate record into account, it seems rather likely that after a couple of years of colder summer temperatures in combination with high late-winter snow accumulation, this site on the lobe can produce ice lenses that persist throughout the year.

We use a similar modeling approach at the borehole site described by IVES (1974) but include a sinusoidal analytical solution of a 1 D temperature profile driven by MAAT and the mean annual ground-surface temperature (MAGST) with associated amplitudes (Fig. 7).

Measured data from 1972 at 3.8 m depth show a wide amplitude over the year with lows at –8 °C to slightly below 0 °C. This is consistent with a sinusoidal analytical solution of a 1 D temperature profile based on the given parameters. Model 1 works with a MAGST equal to the MAAT of 1972. It results in a short phase of temperatures above 0 °C in late August to early September, and it shows mainly very high consistency with the field data. However, we must emphasize that model 1 is driven by a MAGST equal to MAAT, but over the last 10 years MAGST was 1–2 °C

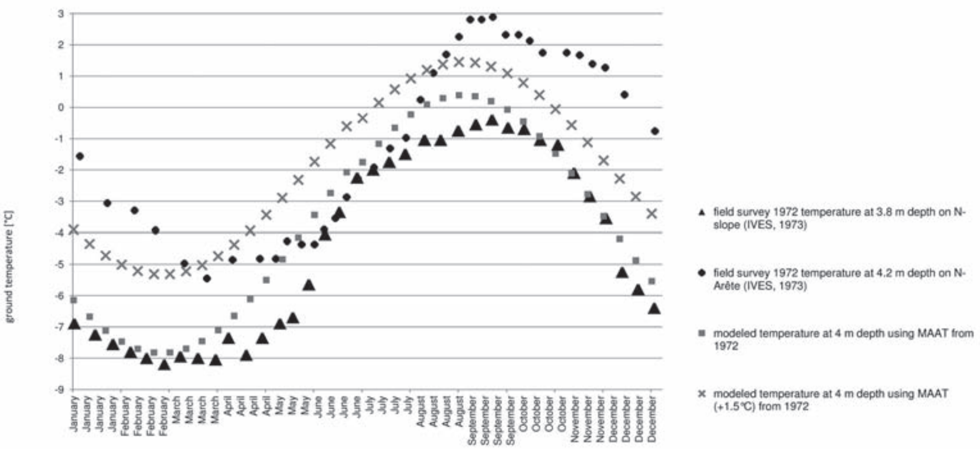

Fig. 7. Annual temperature record at 3.8 m depth measured on a steep north facing slope in 1972 by IVES (1974, black circles) compared with a 1 D model that provides a sinusoidal analytical solution for a 1 D temperature profile in bedrock. The model driven by the mean annual air temperatures (MAAT) from 1972 (gray triangles) and the measured data are in good accordance during the winter months. During the spring and summer months the model provides slightly higher temperatures. This difference may result from an aspect effect for solar radiation on north-facing slopes. Using a mean annual ground surface temperature (MAGST) that is about 1.5 °C lower than MAAT to drive the model (gray squares) would lead to several weeks of unfrozen conditions on Niwot Ridge for 1972 and today.

lower than MAAT (compare Janke et al. 2012). Therefore for model 2 we used a MAGST 1.5 °C higher than MAAT and kept all other parameters unchanged. Results model a period of unfrozen conditions from July until October at 3.8 m depth with a maximum temperature of up to 1.45 °C.

5 *Discussion*

The existence of permafrost over large areas on Niwot Ridge was accepted for many years, and the perceived existence of permafrost influenced research activities in other disciplines like Ecology and Hydrology. Here we carefully evaluate the old permafrost data and compare and contrast with more recent ones.

The rise of summer air temperatures, both at D1 and at the Saddle meteorological station, and the increase of+DD at D1 (Table 1, Fig. 2) over the last several decades, could be interpreted as an impact of climate change on high mountain environments, as documented in other areas of the world (e.g., Harris et al. 2003, Li et al. 2008). Melting permafrost over large areas on Niwot Ridge and Green Lakes Valley (adjacent to Niwot Ridge) could affect the hydrological regime of nearby surface and subsurface waters, both in water quantity and quality over the years. Williams et al. (2006) presented data on a shift in the hydrochemical signal towards higher Ca^{2+} and SO_4^{2-} values and mentioned the melting of permafrost or buried ice in a rock glacier as a possible explanation. Caine (2010) suggested that "*more than half (2.5/4.7 mma^{-1}) of the apparent increase in annual discharge and almost all (2.5/2.6 mma^{-1}) of the increase in late-season streamflow from the alpine part of Green Lakes Valley in the last three decades may have been due to the melting of permafrost ice*".

In order to carefully model future changes in permafrost, it is important to know not only the modern distribution of permafrost but also whether permafrost actually existed widely on Niwot Ridge and in nearby areas such as Green Lakes valley in the recent past. Permafrost was believed to exist over a wide area of Niwot Ridge based on studies from Ives & Fahey (1971) and Ives (1973, 1974), and more recent modeling activities seemed to corroborate this statement (Janke 2005). However, temperature profiles and drilling results down to over seven meters together with geophysical studies at five different sites between 3500 m a.s.l. and close to 3800 m a.s.l. on wet and dry southern slopes, the plateau, and at the rim towards the northern slope of Niwot Ridge yielded negative results for permafrost to date (Leopold et al. 2008a, 2010 and also this study). Where we found ice lenses that formed during the winter, they completely melt out during the summer and fall season. This finding either indicates that permafrost melting has already affected high altitude areas, as suggested by Caine (2010) or that the permafrost distribution on these sites has been overestimated or some combination of both.

A recent study by Janke et al. (2012) along Trail Ridge Road at roughly 3500–3700 m a.s.l. in Rocky Mountain National Park points out that despite the fact that three different permafrost-distribution models indicate permafrost, temperature loggers as deep as 7 m did not provide any indication of freezing conditions throughout the year. This corroborates our data for the Fahey Site. It is also in accordance with a record from the 1970s, when Ives (1973) reported temperatures above 0 °C down to 3–4 in the subsurface at 3485 m a.s.l. and 3490 m a.s.l. Only on the very wet gelifluction lobe did temperatures below 0 °C persist throughout two following summers (Ives & Fahey 1971). Such lobes are limited in distribution, and, thus, are not representative for the area. It must be also noted, their measured temperatures were barely below 0 °C, which is also close to the resolution limit of the analog thermometers used in those days. Taking the 1970s MAAT from the 250 m higher D1 station as the driving parameter for a simple 1 D model for heat flow under transient conditions shows that ice lenses could form and persist throughout the year at that time. The model we used was simple, not taking the various stratigraphic changes and a possible snow cover into account. However, it documents that a few colder years in combination with a high snow accumulation in April and May could probably produce formation of ice lenses that last throughout the year. Sites that provide water during the year are especially likely to reactivate permafrost conditions but they have a limited spatial distribution as noted above.

The second site where permafrost was detected in the 1970s at 3.8 m depth is representative only of steep northern slopes, which are characterized by reduced solar radiation. Furthermore, the site description and the linear trend of the measured data presented by Ives (1974) suggest that this area has bedrock close to the surface. Annual temperature variations penetrate much deeper in rocks (> 20 m) compared to vegetated, soil covered areas that are characteristic for large areas of Niwot Ridge (5–12 m, Noetzli & Vonder Mühll 2010, Warnecke 1997). However, 62 % of the land cover of the adjacent Green Lakes Valley consists of exposed bedrock and talus, compared to only 29 % soil cover, thus permafrost may be more extensive there (Erickson et al. 2005). The sinusoidal analytical solution of a 1 D temperature profile driven by 1972 MAAT results in freezing conditions for most of the year, except for a few weeks in August. Modeled temperatures are below a maximum of 0.5 °C. As there is a rather close relationship between model and field results from October to June, we have confidence in the model even though it is simple. However, from June to the middle of September the measured data of 1972 show a bending curve keeping the temperatures below 0 °C. This could be explained as an effect of aspect slowing down the summer temperatures probably in combination with late winter snow accumulation. Assuming a MAGST with 1.5 °C higher than MAAT, as was the case during the last 10 years at D1 (Janke et al. 2012), the model results in surface temperatures above 1 °C during the summer. This is somewhat corroborated by the ERT surveys around this location (Leopold et al. 2010, and this study) over the last several years, which did not find wet permafrost.

Permafrost sites described by Ives & Fahey (1971) and by Ives (1973, 1974), which lie between 3500 m a.s.l. and 3800 m a.s.l., do not support permafrost at present on flat areas and south slopes. It is important to know that they were marginal sites for permafrost in the 1970s. Due to the rise in temperatures over the last decades during the summers (Table 1, Fig. 2), the two sites remain above 0 °C for several weeks during the summer at 2 m and 4 m depths respectively. However, this does not stop the movement of a gelifluction lobe as its surface shifted at 11.4 m * a^{-1} during 2006–2009, which is slightly faster than during 1963–1967 (9.4 mm * a^{-1} Benedict 1970). It also is important to note that solifluction lobes have only a rather limited spatial significance (max. 16 % of the area on the geomorphic map of Benedict 1970). To us, it seems likely that, apart from north facing slopes and wet sites, in the 1970s many areas on Niwot Ridge below 3800 m a.s.l. may not have had permafrost. Above 3800 m a.s.l. where vegetation and thick sediment cover is more limited, such as the adjacent Green Lakes Valley, climatic conditions seem to support the formation of permafrost at depth below 4 m, a hypothesis that needs to be tested in the near future. Therefore, the possible effects of rising air temperatures on permafrost are restricted to north facing slopes and highest altitudes and must not be assigned to all of Niwot Ridge and surrounding areas below 3800 m a.s.l. However, we have evidence of wet permafrost on some north facing slopes and of buried ice in rock glaciers from geophysical surveys in the nearby Green Lakes Valley (Leopold et al. 2010, 2011), and there are indications of melting permafrost in this area from analyses of the hydrochemical signatures of those surface waters (Caine 2010, Williams et al. 2006).

6 *Conclusions*

Global temperature variations influence alpine permafrost. However, each site must be carefully checked and monitored over a sufficient period of time in order to fully understand variation of the local conditions, including but not restricted to temperature, which influence permafrost genesis before any climate-related conclusion may be drawn.

Our results carefully reevaluate older data and combine them with modern values. Available data from the 1960s and 1970s suggest permafrost based on direct measurements for only two sites, a solifluction lobe and a site on the northern slope of Niwot Ridge. Both sites have a limited spatial significance for the overall Niwot Ridge environment. All other permafrost occurrences in the past have been based upon extrapolation of a linear temperature trend, not on direct measurements. Such extrapolation may be valid for simple bedrock geology but probably not for sites with more complex layers of sediments. Today, we do not find wet permafrost on most sites at Niwot Ridge, except at some north slopes and in the neighboring valleys at higher elevations. These permafrost sites have and certainly will undergo changes due to rising summer air temperatures as documented by Williams et al. (2006) and Caine (2010).

However, degradation and reformation of permafrost conditions in combination with increased gelifluction has been documented for several periods throughout the Holocene (Benedict 1970), and this seems to be a part of the site-specific conditions at Niwot Ridge.

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