Temporal Variability of Alpine Solifluction: a modelling approach

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1 Introduction

Solifluction, the slow downslope movement of thawing soils, is a widespread phenomenon in the alpine ecotone of high mountain areas (Photo 1). It results from the combined, but variable, interaction of frost creep and gelifluction mechanisms (FRENCH 1996; WASHBURN 1979). In the Alps, the distribution of landforms generated by solifluction has been documented by, among others, FURRER (1954, 1965), HÖLLERMANN (1967, 1977) and STINGL (1969). The variable altitudinal distribution of solifluction lobes or sheets, either across a single mountain range or between different regions, early led to the concept of a climatically determined «periglacial altitudinal belt» (BÜDEL 1937; TROLL 1944).

Dating of relict solifluction landforms shows, that several periods of enhanced movement occurred during the Holocene (cf. STEINMANN 1978; GAMPER 1982, 1985; VEIT 1989, 1993 on their work in the Alps; MATTHEWS et al. 1993 for a review of studies in Europe; SMITH 1993 for North American approaches). Such «solifluction phases» frequently did not occur simultaneously with periods of glacial advance or timberline depression. It seems solifluction responds to climatic changes in a different way than glaciers or the timberline. Hence, an analysis of the processes and relevant controlling factors involved in solifluction may lead to the formulation of an approach suitable for the identification and quantification of Holocene climatic fluctuations.

There is a widespread agreement that enhanced solifluction in the past reflects climatic cooling, although knowledge about the precise nature of the dependence of solifluction on climate is still limited (MATTHEWS et al. 1993). As far as we know, there are only three long-term studies investigating the present nature of this relation in non-permafrost, mid-latitude areas – two in the Swiss Alps (GAMPER 1981, 1987; KRUMMENACHER et al. 1998), one in the Austrian Alps (VEIT 1988; VEIT & HÖFNER 1993; VEIT et al. 1995). They suggest that solifluction intensity is strongly related to the annual depth of soil freezing. The studies indicate the relevance of the insulating snow cover in terms of its autumnal onset as well as total duration. Early snow cover may delay or even prevent ground freezing and thus reduce soil movements. At the Swiss site, low winter temperatures enhance frost penetration. At the Austrian site, low summer temperatures additionally induce higher soil movement rates. The explanation offered is that the lower temperatures delay ground thawing prolonging the solifluction period. Findings of such long-term field studies are supported by process studies of solifluction in large-scale laboratory simulations, showing the importance of ground freezing in promoting soil movements (HARRIS 1996). Measurements by MATSUOKA et al. (1997) in the Swiss Alps also underline the dependence of frost-creep type soil movements on the thawing of initially frozen ground.

To clarify the close relation between snow cover, soil freezing and solifluction intensity, a follow-up study was carried out at the Austrian site in 1995 (JAESCHE & HUWE 1997; JAESCHE et al. 1997). A soil physical approach was chosen, water and heat regimes as well as frost heave and subsurface soil movement being monitored on two solifluction lobes. The importance of ground freezing for triggering solifluction movements could be confirmed. The strongest movements generally occur during a period of a few days when the ground ice is melting. They attenuate but continue for several weeks as long as lateral water supply from higher snow patches persists (JAESCHE 1999).

In the study area, present solifluction occurs above 2600 m a.s.l., and leads to the formation of small, mainly nonvegetated solifluction lobes. Densely vegetated and obviously inactive lobes may be found as low as 2300 m a.s.l., representing several Holocene phases of intensified solifluction (VEIT 1989, 1993). This strong 300 m depression of the periglacial belt may be explained in different ways. It might be caused by a marked decrease of mean annual air temperature by 2 °C. But if one assumes a maximum drop in Holocene mean annual air temperatures of only 1 °C (e.g. BUCHENAUER 1990; BURGA & PERRET 1998; LISTER et al. 1998), the belt depression could not have been induced by lower temperatures only. Changes in precipitation totals or annual weather characteristics must also have influenced solifluction.

This paper demonstrates how ground freezing at the Austrian solifluction site varies within a three-year period. Measurements are used to calibrate a physically based soil water and heat model in order to simulate seasonal freezing from daily weather data. The model is applied to explore freezing and solifluction intensity during periods of changed climate and allows quantitative inferences on climatic conditions during Holocene solifluction phases.

Photo 1: Solifluction lobes on the *Medel Spitze* (2670 m a.s.l.), Austria
Solifluktionsloben bei der Medel Spitze (2670 m ü.M.), Österreich
Lobes de solifluxion à la Medel-Spitze (2670 m d'altitude), Autriche
Photo: H. VEIT

2 Methods

2.1 Site description and measurements

The study area is situated in the southern *Hohe Tauern* mountain range (Eastern Tyrolia, Austria) between the *Großglockner* and the *Schober Group* (Fig. 1). Lower parts of the area down to 2200 m a.s.l. are covered by alpine tundra vegetation, higher regions above 2600-2700 m a.s.l. are almost devoid of vegetation cover. Petrographically, the area is characterised as a mixed zone of easily weathering, calcareous mica schists and phyllites. Solifluction processes created lobate features of different sizes. The larger ones can reach a length of more than 100 m, with faces about 0.5-2.0 m high. The lower distribution limit of solifluction lobes is at 2300 m a.s.l. (STINGL 1969). Radiocarbon dating of fossil soils buried by solifluction determined that the big lobes originated mainly during two activity periods, 3350-2800 ^{14}C yr B.P. and around 1250 ^{14}C yr B.P., following an Early- to Mid-Holocene period with stable slopes and soil evolution (VEIT 1993).

Solifluction processes are observed on a monitoring plot at about 2640-2670 m a.s.l. (STINGL & VEIT 1998; VEIT et al. 1995), presumably at their present lower limit of significant activity. The site, with inclinations between 10-20°, faces east to north and is heavily shaded by a steep mountain ridge, especially during winter. The mean annual temperature is about -2 °C, precipitation reaches approx. 1200 mm a^{-1}. Observations were initiated in 1985 and have resulted in a 16-year data set of annual surface movement so far. Movement rates are obtained from regular tachymetric measurements at 7 surface markers, consisting of 20-cm-long PVC rods inserted half-way into the ground. Spatial distribution and variability of solifluction rates at the site were also observed, using at least 90 markers, showing persistent movement patterns at the site during subsequent years (JAESCHE 1999).

Instruments were installed on two solifluction lobes in 1995 in order to monitor soil temperature and liquid water content, as well as frost heave and subsurface movements. Soils show a high stone content of 38-50 % by weight; soil texture is defined as being a sandy loam. Temperature data were obtained using thermis-

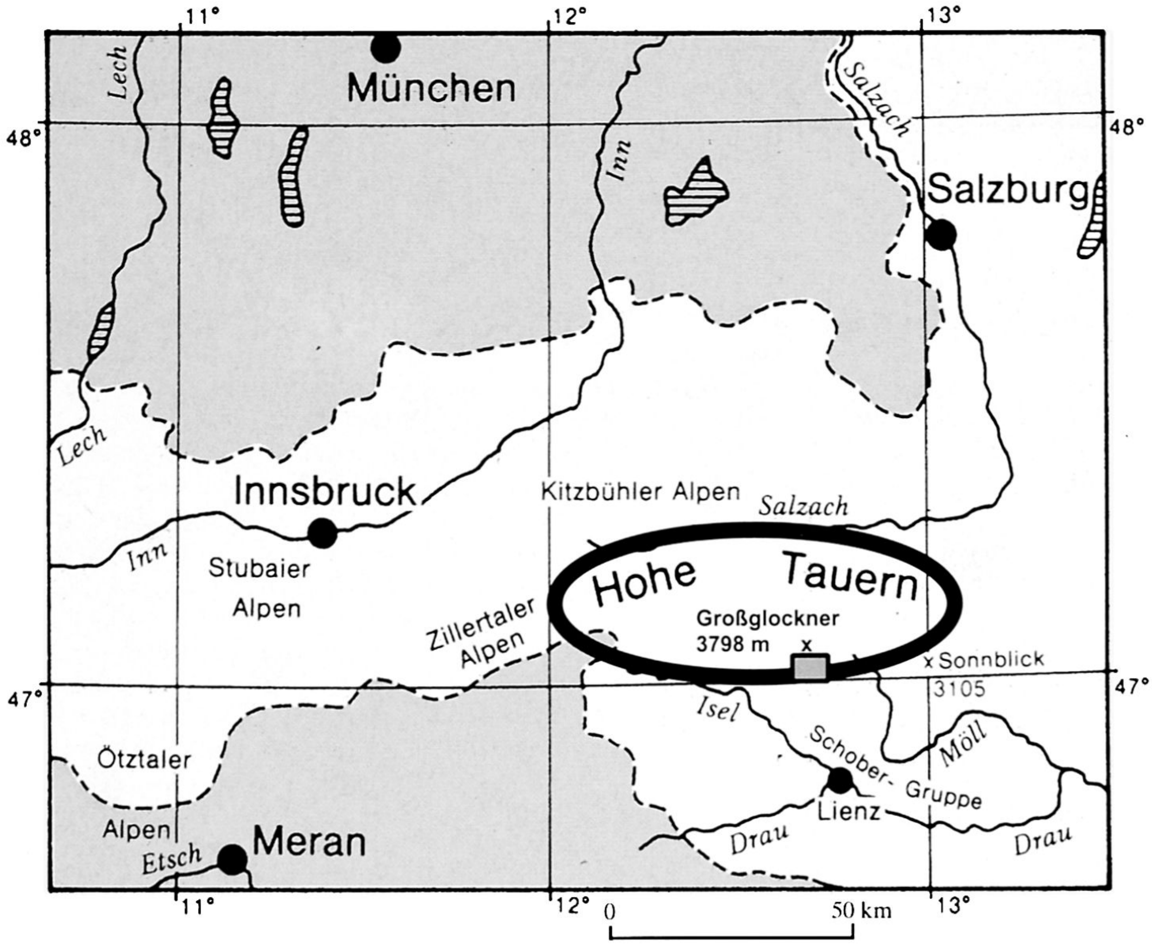

Fig. 1: The study area in the southern *Hohe Tauern* range, Austria
Lage des Untersuchungsgebietes in den südlichen Hohen Tauern, Österreich
Situation du périmètre d'étude dans les «Hohen Tauern» méridionales, Autriche
Source: HÖFNER (1995), modified

tor probes (Fenwal 10 kΩ) at 10 depths between 1 and 120 cm below the surface, and registered with a field data logger (DeltaT DL-2). Water content was registered at 6 depths between 10 and 90 cm using an automated time domain reflectometry (TDR) system (IMKO TRIME-MUX6 with P2Z-probes). During the first winter, water potential was also measured using tensiometers with pressure-transducers. As temperature gradients tend to be minimal during winter and frost depths difficult to determine by the interpolation of temperature data, TDR measurements were chosen to indicate the transition of the soil status from unfrozen to frozen. A comparison of TDR and thermistor data showed a generally good correlation concerning the onset of soil freezing. Daily weather data was delivered from the *Sonnblick Observatory* (3105 m), situated only 10 km east of the site, across the *Möll* valley. Information about the snow cover was obtained from periodical field observations and from calculations described below.

2.2 Model description and applications

The model SOIL (JANSSON 1998) decribes the coupled heat and water transport between atmosphere, snow cover and the soil in the vertical dimension, calculations being based on diurnal precipitation and temperature data. SOIL explicitly considers soil freezing and subsequent changes in thermal and hydraulic characteristics of the soil. It accounts for evaporation, surface runoff and subsurface downslope water flow in the saturated soil, as well as infiltration into the frozen soil through previously air-filled pores. Simulated heat flow takes conduction, convection and energy conservation into consideration. Unsaturated water transport is simulated in terms of the Richards equation. A detailed technical description is found in JANSSON (1994, 1998) and, like the model itself, may also be found on the internet (http:// bgfserver.mv.slu.se/ bgf/ soil.htm). Recent model applications are given by STADLER, FLÜHLER & JANSSON (1997) or STÄHLI, JANSSON & LUNDIN (1999).

Precipitation was assumed to occur as rain above an air temperature of 0 °C, as pure snow below -1°C, and as a variable mixture at air temperatures between. The snowpack is generally treated as a homogeneous layer, with the thermal conductivity being a function of its density (cf. LANGHAM 1981). Snowpack density itself is modified according to the length of time since the last snowfall, the total mass of the snowpack and the liquid water content (JANSSON 1998). Where a snowpack is present, soil surface temperature is calculated assuming steady-state heat flow according to the thermal gradient and thermal conductivity of the snowpack and of the topsoil. If the snow liquid water content exceeds a certain threshold value, soil surface temperature is set at 0 °C as snowmelt conditions are assumed. The surface temperature of both the snowpack and the snow-free soil were assumed to equal air temperature, although the model also includes the possibility of calculating surface temperatures using energy balance approaches. Snow melt was simulated applying a pure degree-day method, using a daily melt rate of 6.1 mm $d^{-1} K^{-1}$, a value taken from independent studies (JAESCHE, BIENERT & HUWE 1998).

The hydraulic characteristics of the soils were described by an adapted Brooks and Corey parameterisation suitable for soil core measurement. Soil freezing characteristics were deduced from TDR field data. For simulations, a 5 m deep soil profile was divided randomly into 11 depth increments between 7.5 to 20 cm thick in the upper metre, the thicknesses of the sections progressively increasing in the lower 4 m. A constant temperature of 2 °C was chosen as the lower boundary temperature.

Model calculations were fed with daily temperature and precipitation data from the *Sonnblick* meteorological station, the data adjusted to take the 450 m elevation difference into consideration by applying values of regional elevation gradients found in literature. Temperature was modified using a constant lapse rate of $6.5 \cdot 10^{-3}$ °C m^{-1} (cf. BUCHENAUER 1990). Daily precipitation rates were reduced by 30%, coming close to the mean annual altitudinal lapse rate of about 100 mm per 100 m (AUER 1992a). The instrumental difficulties involved in the determination of daily precipitation have to be kept in mind (e.g. AUER 1992b). First, the snow-related model parameters were calibrated to reflect measured snow water equivalents and snow height data. Then, unfrozen saturated water conductivity was adjusted according to measured water content during a late-summer period without water input from rain or snowmelt. Finally, the description of water conductivity under frozen conditions, especially during early autumnal snowmelt events and in spring, was defined by visual comparison of simulated and

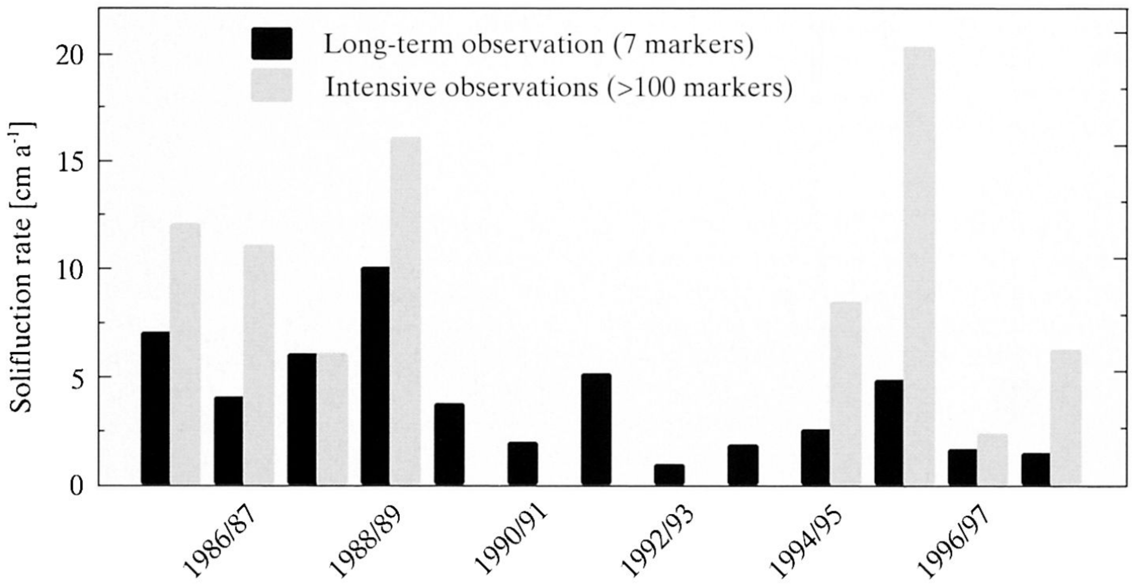

Fig. 2: Mean solifluction rates (median values) for three data sets, using different numbers of movement markers

Mittlere jährliche Solifluktionsbeträge (Medianwerte) aus drei Messreihen mit unterschiedlicher Anzahl an Bewegungsmarkern

Valeurs moyennes annuelles de solifluxion résultant de trois séries de mesures à nombre différencié de marqueurs de mobilité measured temperature and water content time series. These calibrations were initially performed with data for the winters 1995/96 and 1996/97, two periods with very strong and very low ground freezing, respectively. A test with data for the following winter, 1997/98, showed reasonable results and made only minor changes in the model parameters necessary (JAESCHE 1999).

In subsequent simulations, snow, water and temperature regimes at the site for the 13-year period from 1985 to 1998 were reconstructed, again using *Sonnblick* weather data. As an index of freezing intensity, maximum frost depth was obtained by the interpolation of temperature output time series.

In a third step, the complete 13-year set of core weather data was modified to be able to calculate simple climate change scenarios. Monitored temperatures were increased or decreased linearly by 0.65 °C and 1.3 °C. For each temperature level, daily precipitation was additionally scaled by factors of 0.5, 0.75, 1, 1.25 and 1.5 to obtain drier or wetter scenarios. This resulted in 25 scenarios characterised by mean precipitation, temperature and resulting frost depth, the extremes comprising a very warm and wet climate on the one hand, a rather cold and dry climate on the other hand. This approach neglects possible shifts in the seasonal distribution of single variables, but it allows the examination of the effects of climate change with regards to the annual variability of weather data, as can be seen in the 13 annual weather scenario data sets.

3 Results and discussion

3.1 Annual variability of solifluction rates and external control

The 13-year record of mean solifluction movements shows a strong interannual variability (Fig. 2). A series

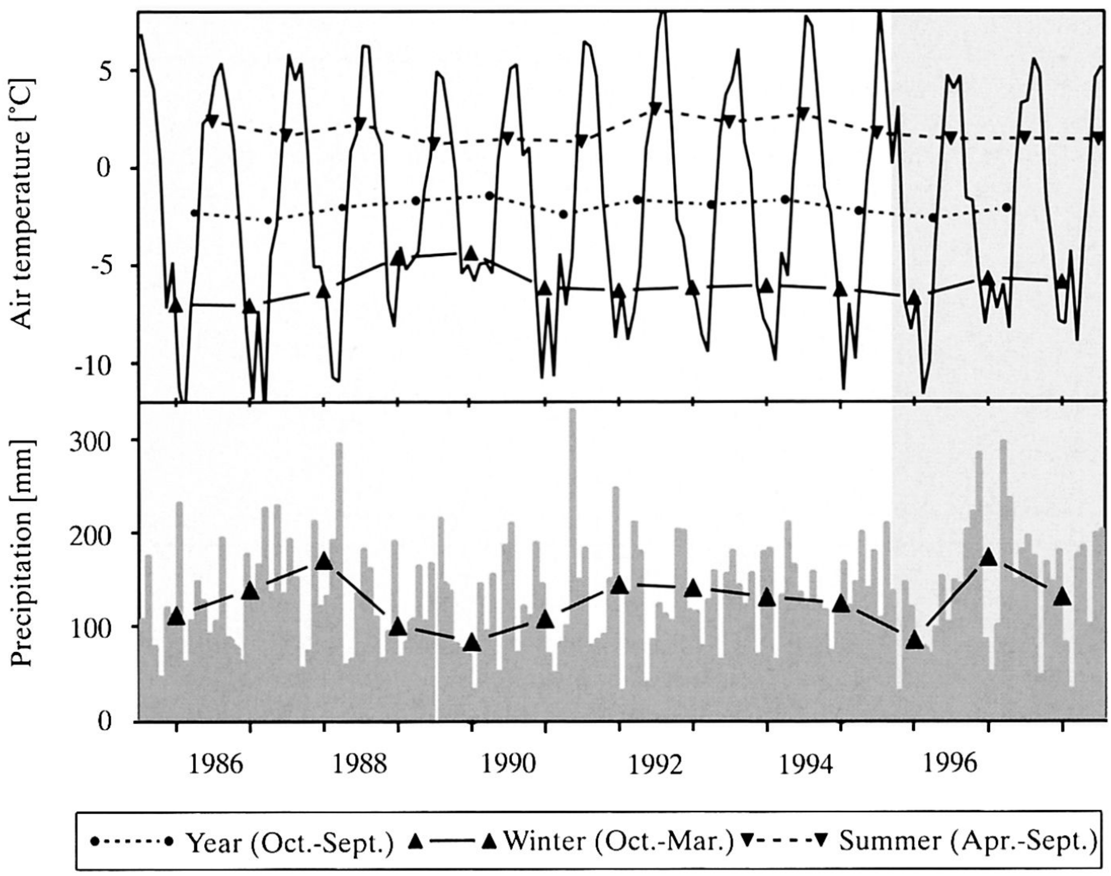

Fig. 3: Monthly mean air temperatures and precipitation sums at the investigation site from Aug. 1985 to July 1998, calculated from measurements at the Sonnblick station. Various seasonal mean values are also given.
Monatliche mittlere Lufttemperaturen und Niederschlagssummen im Untersuchungsgebiet (Aug. 1985-Juli 1998), abgeleitet aus Messungen am Observatorium Hoher Sonnblick. Zusätzlich sind verschiedene saisonale Mittelwerte dargestellt.
Températures de l'air et totaux de précipitations mensuelles moyennes dans le périmètre d'étude (août 1985-juillet 1998), calculées à partir des mesures effectuées par l'observatoire «Hoher Sonnblick». Diverses valeurs moyennes saisonnières sont également indiquées.

of high movement rates, including the maximum value in winter 1988/89, is followed by several lower rates and almost complete inactivity in the 1992/93 period. There is no indication of site disturbance due to marker installation, as was observed in a review of other studies on solifluction (SMITH 1992). The 7 surface markers for long-term observations are in relatively stable regions, while markers used during the two intensive monitoring periods (1985-1989 and 1994-1998) were preferentially positioned in mobile regions. Different inter-annual changes occurred within the two marker groups, e.g. a solifluction decrease was observed between 1996/97 and the next season in the one group, whereas an increase was observed during the same period in the other group. The differing mechanisms of solifluction that might act within these two groups will be discussed in detail elsewhere. Both results indicate the inherent uncertainties present when dealing with mean solifluction rates, for example in comparison with climatic variables as shown below.

Analogous to observations made by VEIT et al. (1995) with a shorter (7-year) data set, the greatest movements, like those in the 1988/89 period, followed a rather warm winter, while the smallest movements occurred after a heavy, yet not unusually cold winter (Fig. 3). Regression analysis of the 13-year data (mean and median values) with various climate indices such as mean monthly or seasonal (e.g. winter) temperatures, generally confirmed the results of VEIT et al. (1995): There is no significant relation between seasonal or annual indices and movement; rather, seasonal weather characteristics, especially during autumn, influence solifluction. Accordingly, a significant correlation of annual movement rates with precipitation totals in October is observed ($r=-0.8$, $p<0.01$). Only a weak correlation ($p<0.05$) is observed between precipitation totals during October and November ($r=-0.6$) and mean temperature in October ($r=0.6$; mean movement only). At first glance, these results seem to oppose soil freezing. But they indicate a stable weather situation

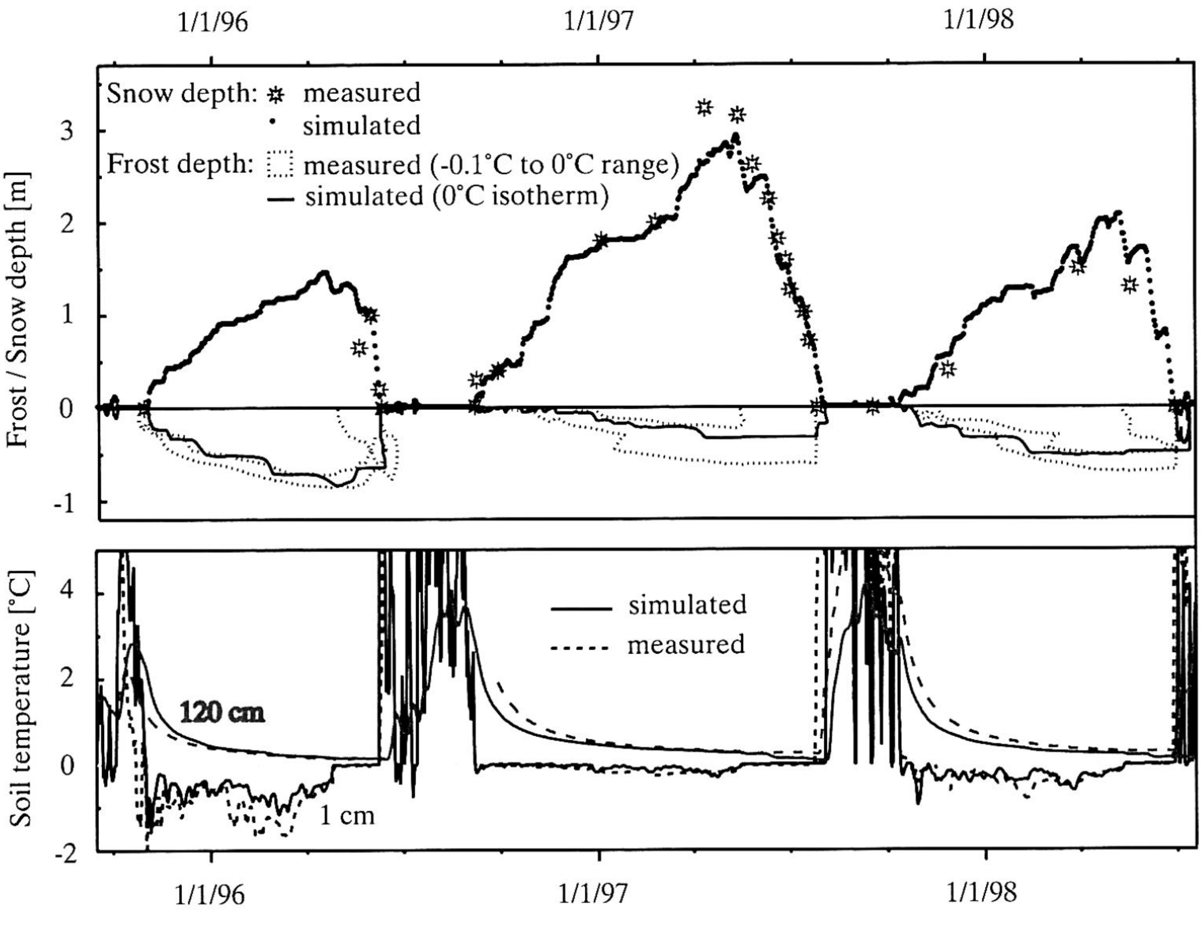

Fig. 4: Snow cover and ground thermal regime at a solifluction lobe at 2650 m a.s.l.: measurements and simulation results

Schneedecke und Bodentemperaturregime an einem Solifluktionslobus auf 2650 m ü.M.: Messdaten und Simulationsergebnisse

Couverture neigeuse et régime de température du sol sur un lobe de solifluxion à 2650 m d'altitude: résultats de mesures et de simulation with temperature inversion and sunshine at mountain sites, precluding the accumulation or even inducing the melting of existing snow cover. Thus, subsequent cold weather, possibly accompanied by only low snowfalls, can induce deeper ground freezing and initiate strong solifluction.

The correlation analysis further shows that cold summers affect slope movements, as low June, June/July and June through August mean temperatures correlate negatively ($r=-0.6$, $p<0.05$) with solifluction rates. This is seen as an indication of prolonged snowmelt periods supporting solifluction by lateral water supply (Jaesche 1999), rather than the hindrance of ground ice melt as proposed by Veit et al. (1995).

The importance of snow depth, especially at the beginning of cold winter conditions, is confirmed by model run-throughs on snowfall intensity: A fourfold increase of daily precipitation during deposition of the first 50 cm of snow (completed within 2 to 10 days) led to a decrease in annual frost depth of up to 50% (Jaesche 1999). Therefore, in order to obtain reasonable values for frost depth and solifluction, it is necessary to consider the precise seasonal course of air temperature, precipitation and snow cover, as will be demonstrated below. Total amounts of winter snowfall or maximum snow depth (as reconstructed by model simulations) do not correlate with solifluction intensity.

3.2 Annual snow cover and frost depth: measurements and model calibration

As is to be expected when observing solifluction variability and taking initial temperature measurements (Veit et al. 1995), snow and soil heat regimes were highly variable during the 1995-98 study period (Fig. 4). A surprising observation is that ground freezing continues or even commences despite snow depths of one meter or more. This is probably caused by the complete shading of the site from November through the middle of February and strong radiation cooling at the snow surface.

Snow and frost regimes were simulated using the SOIL model (Fig. 4). Calibration of the snow sub-model with field observations meant that an additional snow input of 25% was made necessary. This is explained by drifting snow accumulation into the concave-shaped, east (leeward) exposed site. Melt rates during the 3-month winter period of complete shading had to be reduced to 10% (cf. Jaesche 1999). Observed ablation dates at the instrumented site were met within two days. Due to the overestimation of snow settlement and hence snow thermal conductivity by the model's default

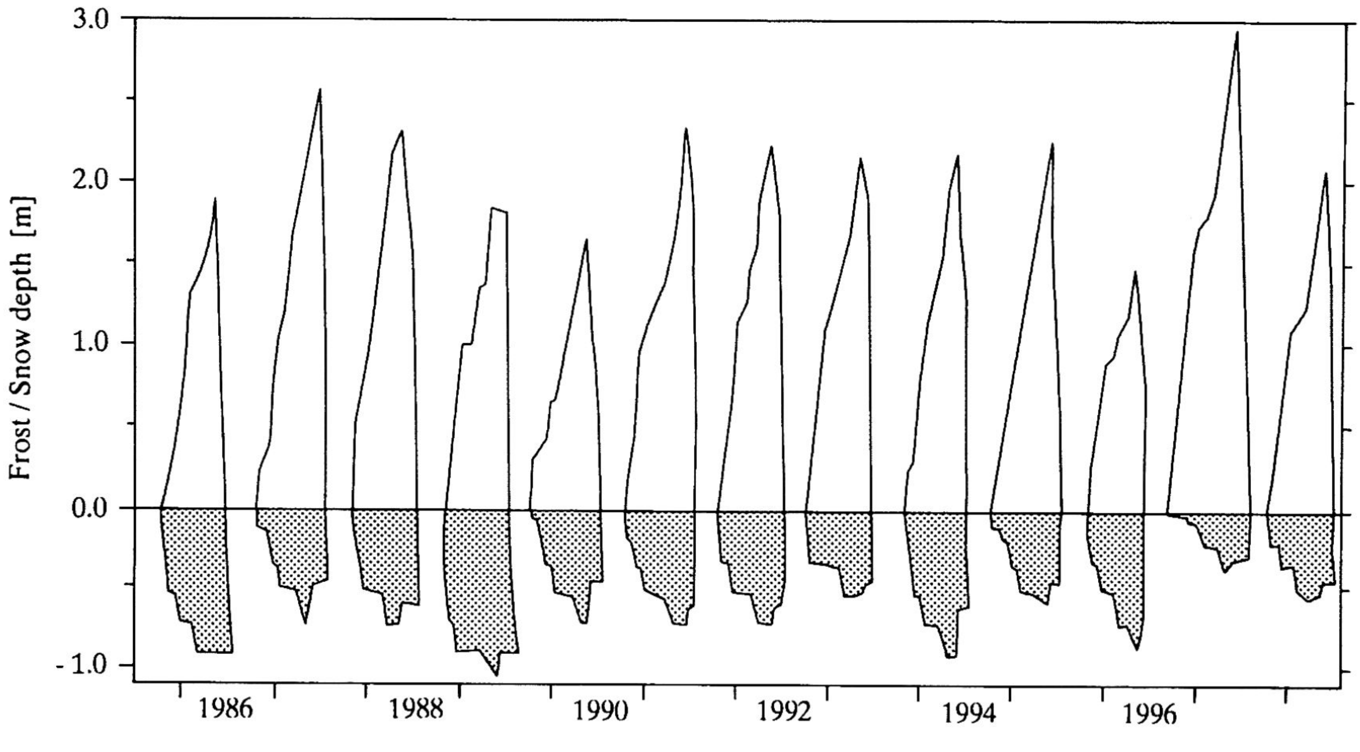

Fig. 5: Simulated dynamics of snow cover and ground freezing 1985-1998
Simulierte Schnee- und Frostdynamik zwischen 1985 und 1998
Simulation de la dynamique de la couverture neigeuse et du gel du sol de 1985 à 1998
Draft by the authors, diagram: L. Baumann

values, especially during winter 1996/97, density-related parameters were modified to describe observed snow depths and soil surface temperatures. Measured saturated water conductivity had to be increased by a factor 10^3 to reflect tension changes during precipitation-free periods. In turn, upward water flow towards the freezing front was reduced. This was necessary to prevent the delay of the frost front progression and the thus reduced total frost depth. Once the calibration had been carried through, model results of soil temperature and frost depth during all three winter periods were in good agreement with field measurements (Fig. 4).

3.3 Long-term (13-year) variability of frost depth and solifluction activity

The successful calibration of the SOIL model provides a reasonable base for ground freezing simulations during the whole 13-year period (Fig. 5). Again, a strong annual variability of snow cover and frost depths may be observed. The calibration period 1995-98 almost covered the full range of frost depths simulated, strengthening the confidence in the validity of this exercise.

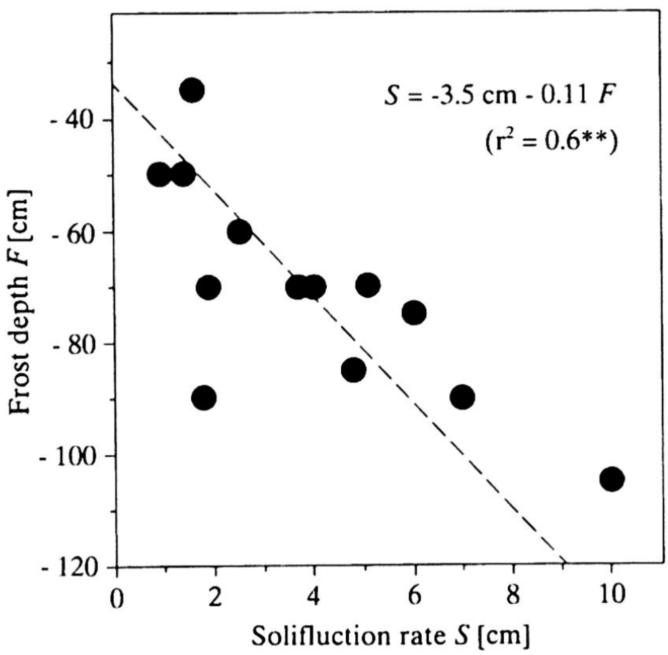

Fig. 6: Relation between annual frost depth (simulated) and solifluction rate (median of 7 marker measurements) between 1985 and 1998

Zusammenhang zwischen jährlicher simulierter Frosttiefe und Bewegungsbetrag (Medianwert aus 7 Einzelmessungen) zwischen 1985 und 1998

Rapports entre la profondeur simulée du gel et le taux de solifluxion (valeur moyenne de 7 mesures différentes) entre 1985 et 1998

Draft by the authors, diagram: L. BAUMANN

While the regression results of climatic variables and solifluction rates shown above could only be interpreted assuming annual variations of ground freezing, the simulation results presented here confirm the relation between annual frost depth and solifluction (Fig. 6). Deep freezing of the ground promotes soil movements. Unexplained variability of solifluction mainly arises from other factors influencing soil mobility, such as soil moisture content influenced by summer snowmelt. It must be noted that the given linear regression is valid only for the measured range of frost depths. It seems possible that an exponential function would better describe the relation, especially at low frost depths. Fig. 6 raises the question of whether a minimum freezing intensity is necessary for solifluction. As independent observations at individual solifluction lobes have shown, no movements occur at zero seasonal frost depth.

Under present climatic conditions, characterised by a mean annual air temperature of -2.1 °C and a mean annual precipitation of 1120 mm, the mean annual frost depth during the 13-year period reaches about 70 cm (Fig. 5). Continual but annually variable solifluction at the investigated site, leads to the formation of lobate surface features very similar to the relict features found at lower elevations. The reason that the relict features are found up to a maximum of 300 m below present solifluction activity cannot be explained alone by minor Holocene temperature changes of 1 °C, as indicated by other proxies. The model described above offers a tool for examining freezing activity and hence solifluction according to changes in mean temperature or precipitation, taking into account their annual variability.

3.4 Frost depth under changed climate scenarios

Similarly to the model results described in the preceding section, Figure 7 shows simulated snow and resulting frost depths for 13 winter periods, however with the focus on a climate change scenario moving towards colder and drier conditions. This is achieved by running the model with modified input data: daily temperatures were reduced by 1.3 °C, daily precipitation rates by 50%. The changes result in drastically enhanced ground freezing, often reaching a depth of two metres. Except in one summer, the durations of the snow-free periods are long enough for ground ice melt to set in, preventing the occurrence of permafrost formation. Changed climate affects freezing in different years to different degrees, e.g. by 200% in 1986/87 and by only 50% in 1993/94. Mean frost depth simulated under these specific cold/dry conditions is 155 cm.

Analogous to this simulation, mean 13-year frost depths were calculated according to a broad range of climate scenarios. Figure 8 summarises the different combinations of temperature and/or precipitation

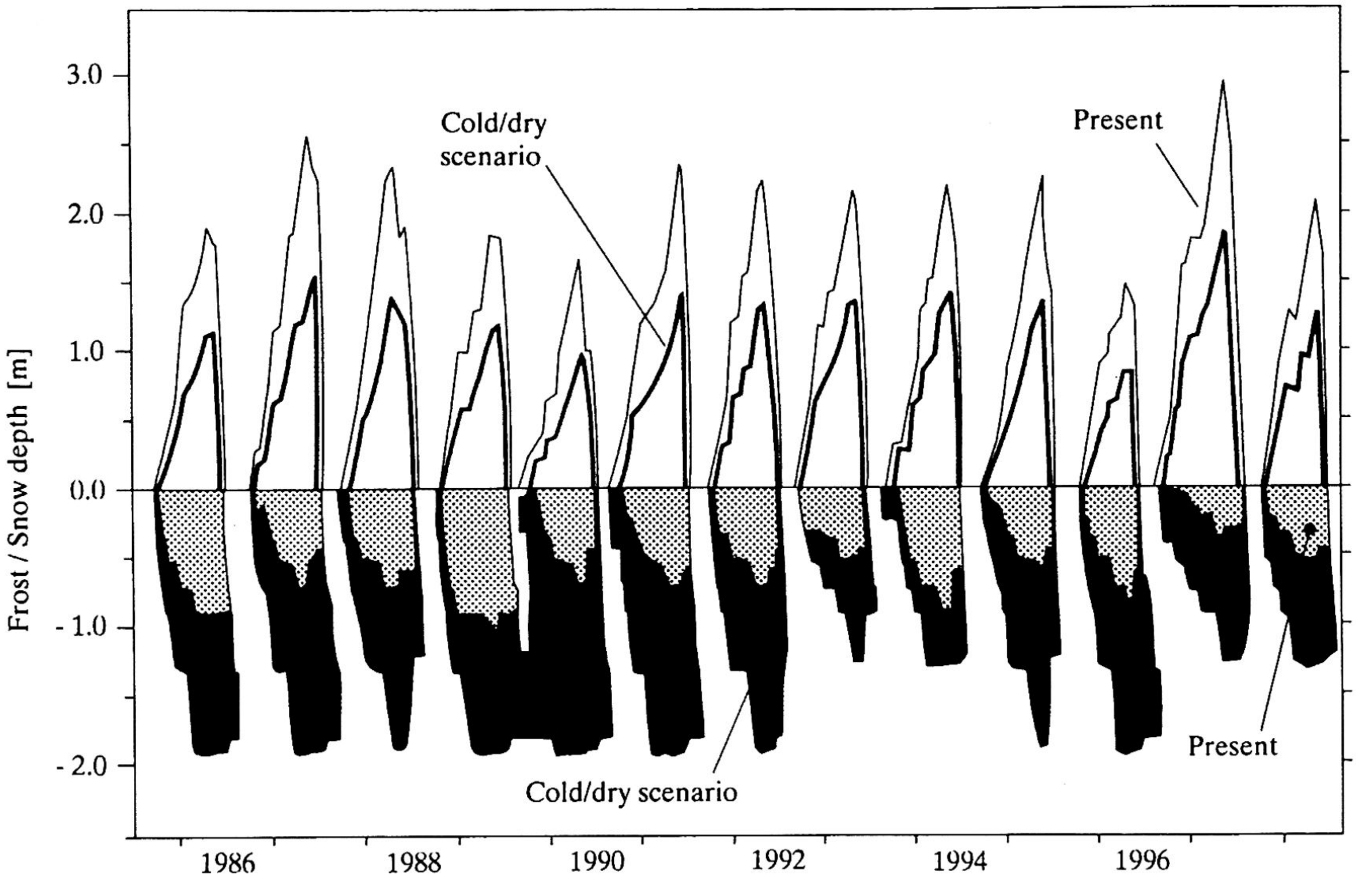

Fig. 7: Simulated snow cover and ground freezing under cold/dry climatic conditions, based on modified 1985-1998 daily weather data (air temperature reduction ΔT = -1.3 °C, precipitation reduction ΔP = -50%). Present conditions are also given (cf. Fig. 5).
Simulierte Schnee- und Frostdynamik unter kalt-trockenen Klimabedingungen, berechnet auf Basis modifizierter täglicher Wetterdaten 1985-1998 (Reduktion der Lufttemperaturen ΔT = -1.3 °C bzw. Niederschläge ΔP = -50%). Zum Vergleich sind die Verhältnisse unter aktuellen Bedingungen angegeben (vgl. Fig. 5).
La simulation d'une dynamique nivale et de gélivation dans des conditions climatiques froides et sèches, calculées sur la base de données météorologiques quotidiennes relatives à la période 1985-1998 (réduction des températures de l'air ΔT = -1.3°C, respectivement des précipitations ΔP = -50%). A titre comparatif, nous indiquons les conditions actuelles (cf. fig. 5).
Draft by the authors, diagram: L. Baumann

changes applied and shows the resulting 13-year mean frost depths. The heaviest freezing occurred in the cold/dry scenario presented above (Fig. 7); mean frost depth under present conditions (Fig. 5) is to be found in the centre of the figure. Though individual years had shown different reactions to changed input data, there is a significant increase of long-term mean frost depth with decreasing temperature or precipitation. Contrary changes in climate variables, though, may balance each other to leave mean frost depth unchanged. This relation is approximated by a bivariate linear regression model, applied to the absolute values of mean temperature and precipitation, as

(1) $F = -100 + 19\,T + 0.059\,P$ ($r^2 = 0.92$, $p<0.001$)

with F being mean annual frost depth (in cm), T mean annual air temperature (in °C), and P mean annual precipitation (in mm).

Recalling the close relation between frost depth and solifluction, the above results make observations about Holocene solifluction and climate variability possible. Colder periods are not necessarily to be associated with intensified solifluction, in particular if precipitation increases simultaneously. Under such conditions, though, glacial advance is possible. Or to put it another way, drier periods may enhance solifluction, while causing glacial retreat, without any temperature changes. As was mentioned before, it is not possible to deduce Holocene temperature changes from field observations of solifluction features only. However, by making use of additional information from independent proxy data, e.g. studies on rock glaciers or timber-

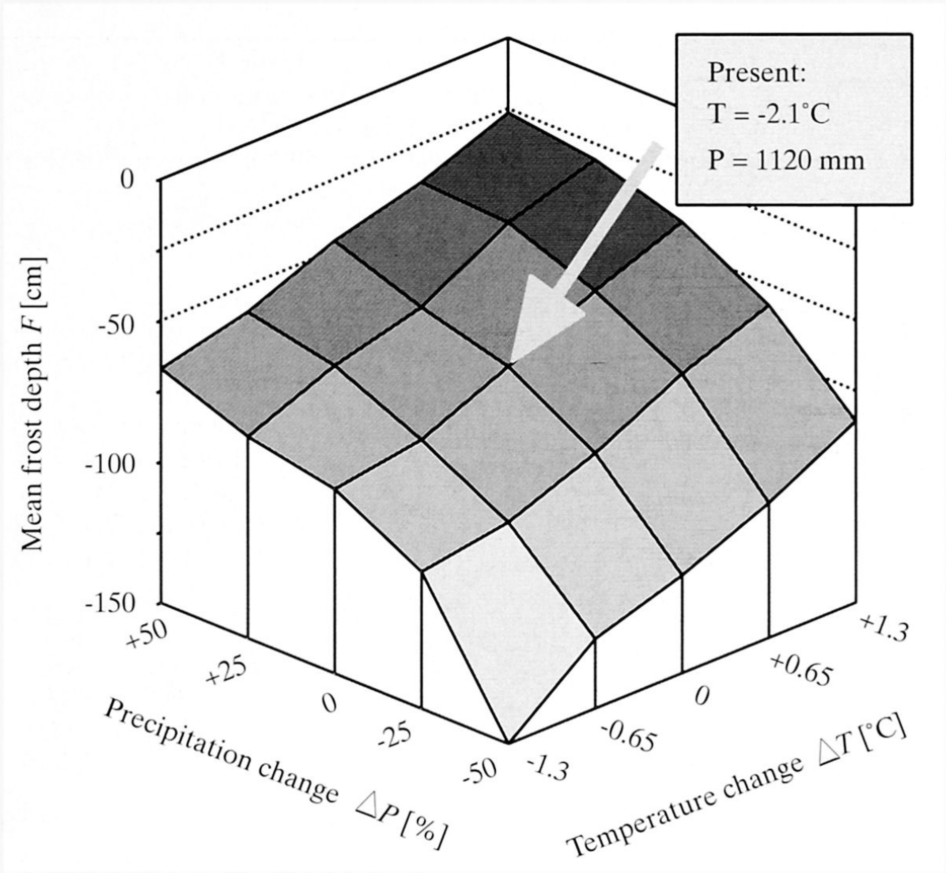

Fig. 8: Mean simulated frost depths occurring under systematically varied climatic conditions (see text)
Mittlere simulierte Frosttiefen unter systematisch variierten Klimaszenarien (vgl. Text)
Profondeurs moyennes simulées du gel sous des scénarios climatiques variés systématiquement (cf. texte)

line, the precipitation regime during periods of intensified solifluction phases may be reconstructed.

Maximum depression of Holocene solifluction in the investigated region of the *Hohe Tauern* by about 300 m, compared to its present distribution, may be used as an example. If Holocene mean annual air temperatures never decreased by more than 1 °C, the temperature belts shifted by 150 m at most. Solifluction occurred at sites situated another 150 m lower or 1 °C warmer than today (T = -1.1 °C). Assuming that the solifluction process was characterised by the same medium frost depth observed today (F = -74 cm), graphic illustration (Fig. 8) or use of the regression model (Eq. 1) reveals a precipitation decrease of 325 mm or 29% in comparison to the present value. Besides this, there is of course still the possibility of considering a greater temperature variability during the Holocene (e.g. a warming of almost 2 °C is documented for the period since 1864 A.D. for Switzerland; Baeriswil et al. 1997) to explain the strong depression of the periglacial belt (Veit 1993). By the fact that the glacier equilibrium lines show minor variations (±100 m), reduced precipitation is indicated. Furthermore, it is possible that the calculated 325 mm precipitation reduction for the Holocene period may be partially explained by the effects of the vertical precipitation gradient.

4 Conclusions

Field observations of past and present alpine solifluction, in combination with intensive monitoring and the simulation of snow depth and soil heat regimes at a site affected by solifluction, represents a new and promising approach towards reconstructing Holocene climate. Although annual movement rates are highly variable and strongly controlled by both the weather conditions during autumn and snow cover variation, long-term solifluction activity clearly responds to climatic change. Solifluction activity is closely linked to the seasonal frost depth. The proposed relation between mean solifluction, temperature and precipitation at a research site in the eastern Alps may be used to explain variations between fluctuations of solifluction and snow or timber line, or even allow quantification of precipitation during Holocene solifluction phases. However, it is necessary to deduce mean temperature data from other sources.

Based on this general approach, future work will have to focus on the calculation of Holocene solifluction rates and the detection of altitudinal variations. The monitoring of soil heat regimes and solifluction on slopes with different exposition, as well as research of solifluction in various climatic regions is necessary to expand the applicability of the model.

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Summary: Temporal Variability of Alpine Solifluction: a modelling approach
Holocene periods of enhanced solifluction offer new paleoclimatic information. Long-term observations of present solifluction variability and process studies on movement mechanisms, as well as model simulations of the soil heat and water regimes, show the dependence of solifluction on ground freezing. The annual variability of both processes is strongly controlled by weather and resulting snow conditions immediately before and at the beginning of the winter frost period. Simulated long-term variations during different paleoclimatic scenarios are regulated by both mean precipitation and temperature changes. Quantitative reconstruction of Holocene precipitation during maximum altitudinal depression of solifluction is shown.

Zusammenfassung: Zeitliche Variabilität alpiner Solifluktion: ein Modellierungsansatz
Die Untersuchung holozäner Solifluktionsphasen bietet einen neuen Zugang zu paläoklimatischen Informationen. Langzeitbeobachtungen heutiger Solifluktionsbeträge, Prozeßstudien solifluidaler Bewegungsmechanismen und Modellsimulationen des Bodenwärmehaushalts zeigen die Abhängigkeit der Solifluktion von Bodenfrost. Ihre jährliche Variabilität wird im

Wesentlichen durch die Witterungsbedingungen und die Schneebedeckung unmittelbar vor und zu Beginn der winterlichen Dauerfrostperiode gesteuert. Simulierte längerfristige Abweichungen der Bodenfrostmächtigkeit unter verschiedenen paläoklimatischen Szenarien werden gleichermaßen von Änderungen im Temperatur- als auch im Niederschlagsregime beeinflußt. Als Anwendungsbeispiel der Modellrechnungen wird die Quantifizierung holozäner Niederschläge bei maximaler Höhendepression der Solifluktion vorgestellt.

Résumé: La variabilité temporelle de la solifluxion alpine: une approche modélisée

L'étude des phases de solifluxion propres à l'époque holocène offre une nouvelle approche à des informations paléoclimatiques. Des observations à long terme des processus actuels de solifluxion, des recherches relatives aux mécanismes de mobilité solifluidale et des simulations modélisées du comportement de la chaleur du sol révèlent la dépendance de la solifluxion du gel du sol. Leur variabilité annuelle s'explique essentiellement par les conditions météorologiques et la couverture neigeuse immédiatement avant et au début de la période hivernale de gel continu. Des variations simulées spécifiques à long terme de la puissance du gel du sol selon des scénarios paléoclimatiques différenciés sont influencées autant par les variations du régime des températures que par celles du régime des précipitations. Comme application concrète des calculs de modélisation, nous avons choisi l'exemple de la quantification de précipitations holocéniennes au moment d'une dépression maximale d'altitude de la solifluxion.

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