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SHORT PAPER

The Alpine ''Iceman'' and Holocene Climatic Change

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The finding of a prehistoric mummified corpse at the upper edge of the accumulation area of an alpine glacier, together with its unique set of artifacts, provided new information on glacier dimensions during the little-known phases of major glacier shrinkage that characterized the warmest parts of the Holocene. The sudden burial of the corpse in a permanent snow cover occurred 5300–5050 cal yr B.P., indicating a significant climatic change that induced glacier expansion at the beginning of Neoglaciation. New geomorphologic data and two AMS ^{14}C ages from buried soils suggest that the present glacier size, following over 100 yr of shrinkage, is comparable to that immediately preceding Neoglaciation. Therefore, we can deduce that the current global climatic warming may have interrupted the environmental conditions prevailing in the Alps during Neoglacial time, restoring characteristics similar to those prevailing during the *climatic optimum* that were never achieved during the second half of the Holocene.

In late summer 1991, the marked ablation of a small glacier near the Similaun Hut, in the Tyrolean Alps (Figs. 1 and 2), brought the mummy of a prehistoric man to the surface (Höpfel *et al.*, 1992; Barfield *et al.*, 1992; Egg *et al.*, 1993; Bahn and Everett, 1993; Spindler, 1994; Barfield, 1994; Spindler *et al.*, 1995). The site is located between the Ötztaler and Venoste Alps, on the northern slope of the divide, about 100 m from the Austrian border in Italian territory near the Giogo di Tisa (Hauslabjoch, 3280 m). The preservation of the corpse was possible thanks to its location in an almost horizontal gully in which it remained motionless, frozen to the ground in cold ice. The corpse of the ''Iceman'' is the highest prehistoric find from anywhere in the Alps (Barfield, 1994); it was endowed with a unique archeological collection of several exceptionally preserved items of clothing and equipment. The mummy's ^{14}C age (from 4500 ± 30 to 4580 ± 30 yr B.P.), corresponding to 5300–5050 cal yr B.P. (Spindler, 1994; Bonani *et al.*, 1992, 1994; Spindler *et al.*, 1995; Stuiver and Reimer, 1993), is older than expected on the basis of the accompanying tools (Barfield, 1994). The find is one of the most sensational archeological discoveries ever and is a real breakthrough for the archeological and paleoanthropological sciences. Furthermore, its geomorphic setting is an invaluable aid in comprehending the alpine environmental and climatic history.

The small glacier that trapped and recently revealed the famous Iceman lies on the northern slope of the alpine divide (Figs. 1 and 2). Until the 1970s, this glacier was part of Niederjoch Glacier (Vedretta di Giogo Basso), a composite alpine glacier that descends northward toward the Nieder Valley below. Between 1910 and 1982, the terminus of Niederjoch Glacier retreated about 900 m (Grove, 1988). The significant shrinkage of the glacier in recent years has dramatically reduced and thinned the glacier's upper part, where increasingly larger areas of rock are being exposed. In the area around the pass between Tisa and Nieder valleys, snow patches and glacierets are separated by annually changing expanses of ice-free terrain.

During the last glacial maximum (LGM), the entire area was completely ice- and snow-covered, apart from narrow and steep *arêtes* and horns that characterize the alpine watershed along the Italian–Austrian border. In the Hauslabjoch area, a sharp trimline divides the uppermost frost-shattered craggy slope segments and parts of serrated crests from lower slopes and crests smoothed and rounded by glacial erosion (Fig. 3). This trimline marks the maximum glacier limit reached during the LGM and probably during lateglacial readvances. In fact, in the uppermost part of the

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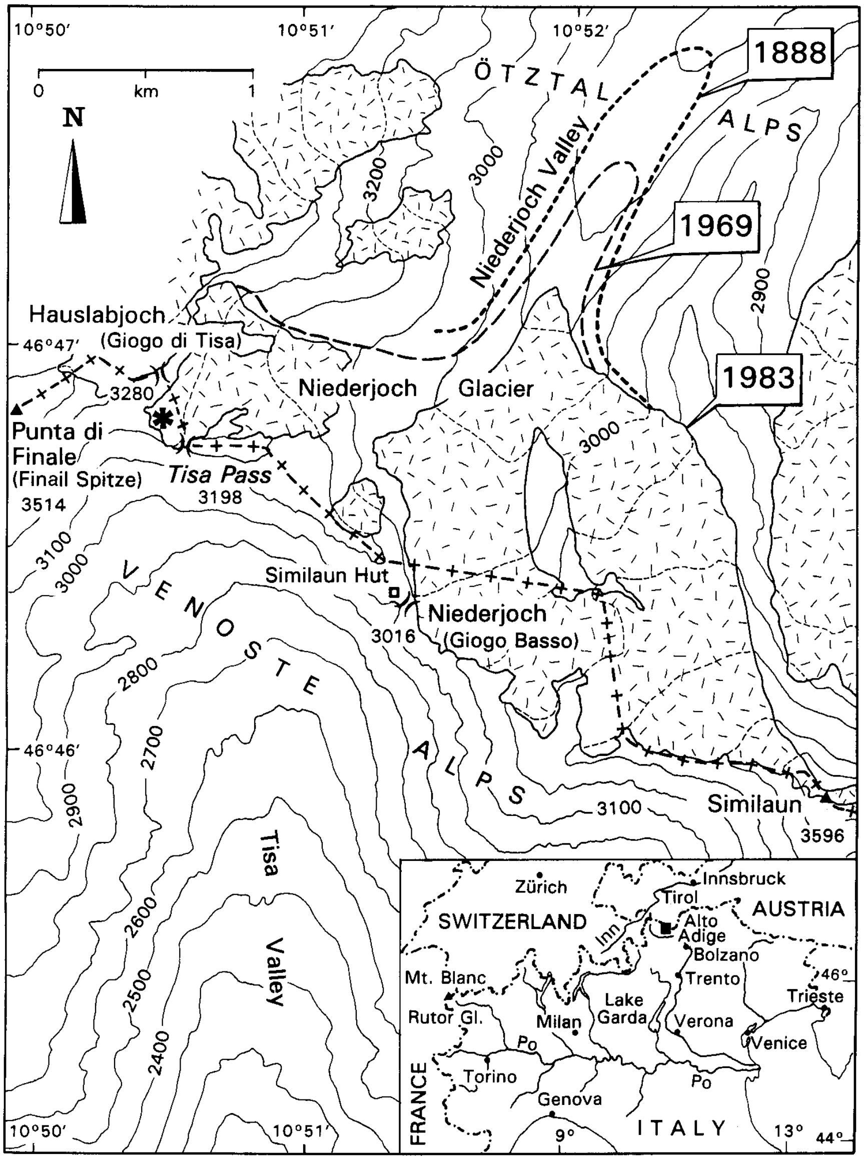

FIG. 1. Map showing location of glacier limits (in 1983) and selected contour lines. Redrawn after the map ''Similaun'' 01203 of the Provincia Autonoma di Bolzano, Alto Adige, at an original scale of 1:10,000, based on aerial photographs taken on September 28, 1983. Other numbers in boxes indicate Niederjoch Glacier frontal positions in 1888 (from sheet 173-Sölden of the Provisorische Ausgabe der Österreichischen Karte 1:50,000) and 1969 (Cime Nere 3 II NE at an original scale of 1:25,000, Italian Military Geographic Institute).

accumulation basins, glaciers sustained approximately the same level during Pleistocene glacial stages (Porter, 1975; Porter and Orombelli, 1982). The elevation of the trimline along the crest profile, as defined by the lower limit of rocky pinnacles and the upper limit of *roches moutonnées,* ranges from 3060 m NW of the Similaun Hut to 3400 m on Punta di Finale (Finail Spitze). The upper trimline can also be recognized locally as a marked weathering line that separates an upper strongly oxidized and rubified surface from a lower weakly oxidized one.

In addition to the LGM trimline, a second one, developed at lower elevations on the *roches moutonnées* eroded during LGM and late-glacial time (Fig. 3), dates to the Holocene. It is defined by an abrupt change in lichen characteristics: the lichens are large, well-developed, and form a dense cover above the trimline but are less common and smaller below. Furthermore, differential weathering has produced rugged surfaces with quartz minerals standing in relief above the trimline, whereas below, fine glacial striations are preserved on the rock faces. Above this lower trimline *Rhizocarpon geographicum* thalli with maximum diameter over 100 mm can be considered >400 yr old on the basis of the growth

FIG. 2. The *Tisa Pass* between Venoste and Ötztal Alps, a photograph taken from the Hauslabjoch (Giogo di Tisa) looking SE. The marked shrinkage of the upper portion of Niederjoch Glacier (in the foreground) in 1991 revealed the corpse of the prehistoric Iceman (in the middle of the photograph, to the left of human figures); the Similaun Group is seen on the left (July 1994).

curve developed by Orombelli and Porter (1983). Below this trimline, the maximum thalli diameters are much smaller (ca. 40 mm) and comparable to those growing on post-1850 surfaces in the Alps. Therefore, this lower trimline marks the ''Little Ice Age'' (LIA) upper glacierization limit (locally not more than 15 m above the present glacier surface, Fig. 4) which generally corresponds to the maximum Holocene glacier elevation.

No soil was found above the LGM trimline. The best-developed soils of the area are found between the LGM trimline (Fig. 3) and the Holocene trimline, in the depressions among the *roches moutonnées* between 3000 and 3160 m (A/B2/B3/C1 profile up to 40 cm thick); these are very similar to Holocene soils that developed in the alpine environment since deglaciation. Below the Holocene trimline, in similar topographic situations, A/C1 inceptisols similar to those developed on 19th century moraines are found (Fig. 4).

A discontinuous buried soil was found near the pass at the head of the Tisa Valley (*Tisa Pass*) in a small ice-free area at 3215 m, 5–6 m below the Holocene trimline (Figs. 3 and 4). Beneath an A/C profile 12 cm deep, developed on coarse gravelly sand with angular clasts of local provenance, a buried A/B3/C/R profile 37 cm deep is present. The base of the buried A horizon has a ^{14}C age of 5615 ± 55 yr B.P. (GX-20678-AMS; 6450–6300 cal yr B.P.). Nearby, another buried organic silty level, discontinuous and only 3 mm

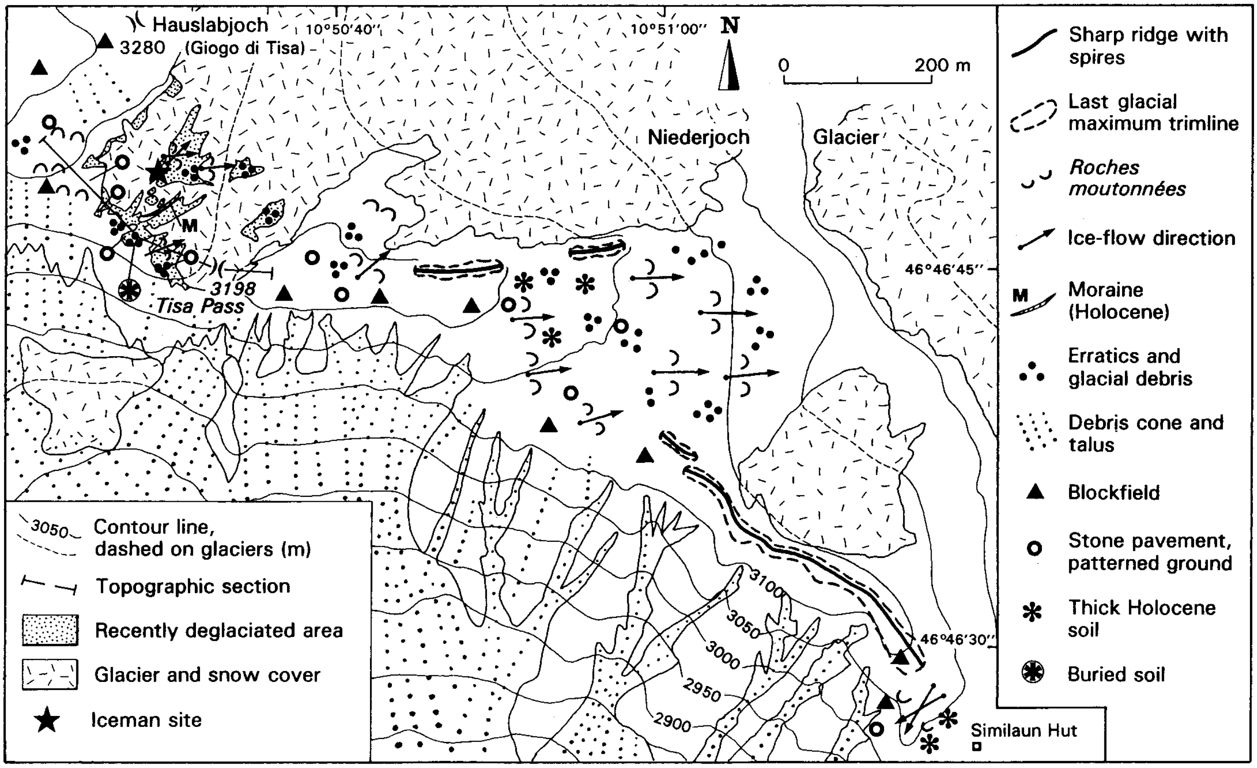

FIG. 3. Geomorphic sketch map of the Hauslabjoch area. During the last glacial maximum (ca. 18,000 ^{14}C yr B.P.), the alpine divide was completely ice- and snow-covered, apart from narrow arêtes and horns. At 5300–5050 yr B.P., the Iceman was buried by snow, from which he only emerged in 1991.

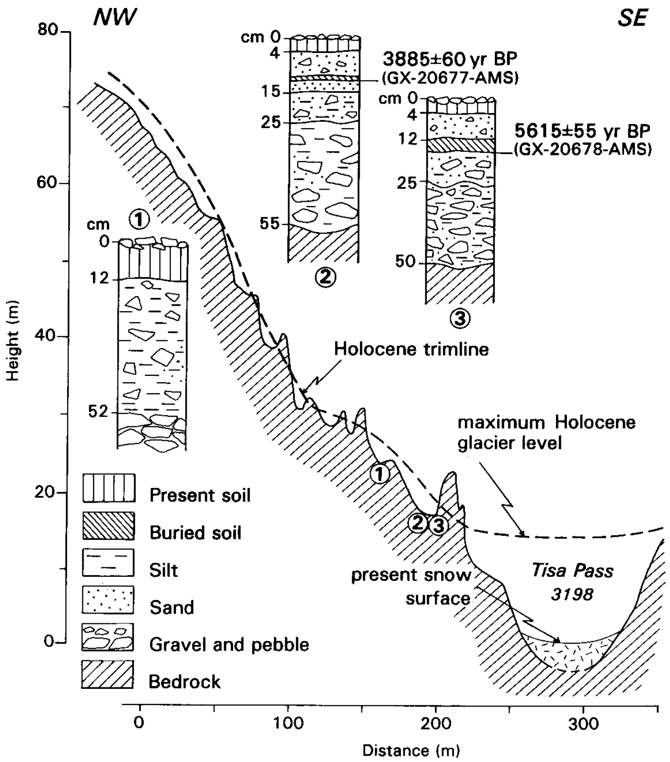

FIG. 4. Topographic section of the uppermost accumulation area of Niederjoch Glacier, near Tisa Pass (see Fig. 3 for location of the section and of the Iceman site). Position of ^{14}C AMS dates from buried soils are shown in soil profiles (1, 2, and 3). The highest part of the accumulation area, where the Iceman came to light, was deeply covered with ice and snow during the Little Ice Age. More than a century ago, this ice cover started thinning and now has reached the same level as at the moment of the Iceman's burial.

thick, has an age of 3885 ± 60 yr B.P. (GX-20677-AMS; 4416–4158 cal yr B.P.). Considering the ''residence time'' effect, pedogenesis began before the oldest age obtained for the deepest soil. The thickness of the A horizon indicates that its development occurred over at least 5–12 centuries, as can be inferred by the age/depth gradient of similar soils in alpine environments (Matthews, 1993; Pelfini, 1995). On the other hand, the thinness of the younger organic layer documents a shorter snow-free period.

Between 9000 and 5000 yr B.P. the mountain glaciers were smaller than in the second half of Holocene, although their extent, particularly in their uppermost portions, is unknown (Porter, 1975; Porter and Orombelli, 1985). Whereas the phases of climatic deterioration and maximum glacier extension are documented by terminal and lateral moraine systems, the most contracted glacier limits are poorly known.

The oldest buried soil in recently deglaciated areas at Hauslabjoch documents that at about 6450–6300 cal yr B.P. (GX-20678-AMS), and for several centuries after, an ice-free upper peripheral belt allowed the accumulation of organic matter in a thicker and more developed soil than that covering the post-LIA deglaciated surfaces.

Furthermore, in the western Alps a sequence of 30 ^{14}C dates (Porter and Orombelli, 1985; G. Orombelli, unpublished data) from a buried peat exposed at the terminus of Rutor Glacier (Fig. 1) in the 1970s proves that this glacier was less advanced than at present between 10,270–9955 (9070 ± 120 yr B.P., GX-14743) and 5740–5605 cal yr B.P. (5045 ± 90 yr B.P., GX-15490; 4945 ± 65 yr B.P., UZ-2790). The glacier advanced sometimes after 5740–5605 yr B.P., burying the peat; the conditions necessary for peat production were never again restored, suggesting that the area possibly was covered by the glacier during the second half of the Holocene until the 1970s. The Rutor Glacier advance is thought to correlate with the phase of increased snow deposition in the accumulation area of the Niederjoch Glacier that buried the Iceman.

As widely recognized (Spindler, 1994; Barfield, 1994), the exceptional state of preservation of the Iceman and of his artifacts requires that he was rapidly entombed at the time of his death and remained so until he was discovered. We therefore deduce that during the past 5000 yr in this area conditions of greater glacier thickness and extent have prevailed. The sudden burial took place at the end of an ablation season, the time of death being revealed by the vegetal material extracted from the glacier (Egg *et al.*, 1993; Spindler, 1994). The corpse remained completely covered throughout every ablation season until 1991, although brief phases of thinning snow cover could have occurred at times in the past creating small ice-free patches at the outer edge of the accumulation area, as documented by a buried organic horizon that dates to 4416–4158 cal yr B.P. (GX-20677-AMS; see soil 2 in Fig. 4).

Thus, the Iceman reveals that at about 5300–5050 cal yr B.P., a rapid climatic change took place, producing a persistent snow cover on previously deglaciated areas; this can only have been caused by a newly established regime of positive mass balance with a sudden and persistent lowering of the equilibrium-line altitude. This deterioration in climate marks the beginning of Neoglaciation (*sensu* Porter and Denton, 1967) in the Alps, which induced a glacier expansion, as is well documented at Rutor Glacier where the front advanced after 5740–5605 cal yr B.P. (UZ-2790).

This event can also be recognized in other paleoclimatic records. Significantly, the Iceman's date of burial coincides with an abrupt increase in atmospheric CH_4 concentration measured in the GRIP ice core (Blunier *et al.*, 1995) at 5200–5000 yr B.P. (Fig. 5), considered indicative of a humidity increase in middle to high latitudes of the Northern Hemisphere. Furthermore, it corresponds to a oxygen-isotope variation in the Renland ice core, Greenland, near the end of the Holocene climatic optimum (Larsen *et al.*, 1995). Beginning about 5000 yr B.P., the methane (GRIP) and $\delta^{18}O$

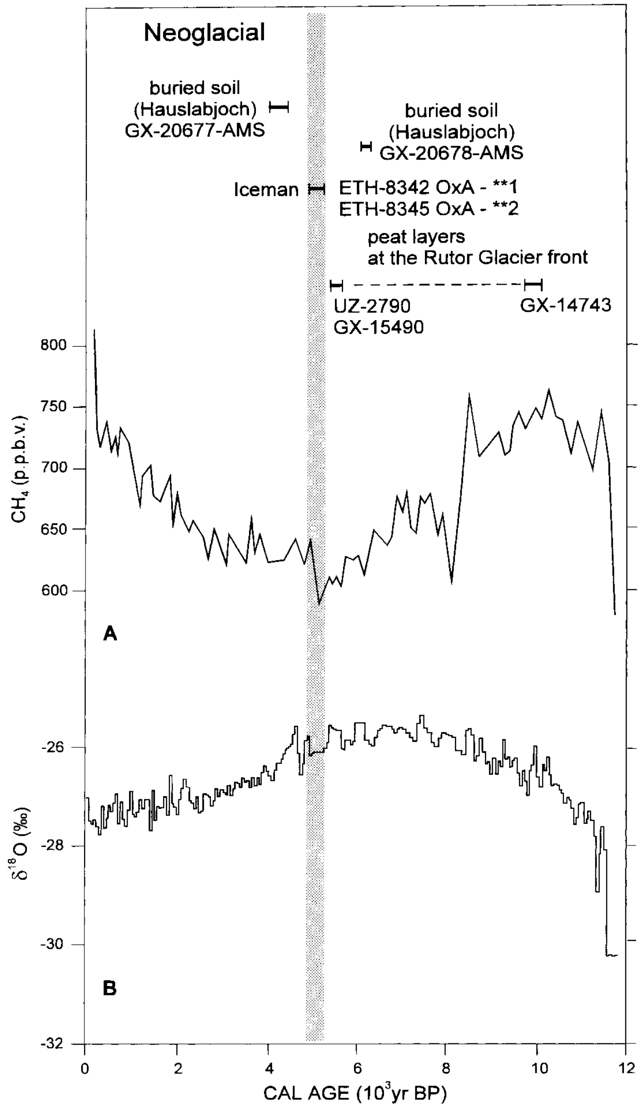

FIG. 5. Calibrated ^{14}C ages from Hauslabjoch and Rutor Glacier plotted with respect to (A) the mean atmospheric methane concentrations from the Greenland ice core GRIP and Eurocore over the past 12,000 yr (Blunier *et al.*, 1995) and (B) with the Holocene oxygen-isotope variations in the Renland ice core, Greenland (Larsen *et al.*, 1995). The dates from buried soils at Hauslabjoch document phases of shrinkage of the accumulation zone and organic matter deposition in marginal temporary ice-free areas. The dates from Rutor bracket an interval of reduced extent of this glacier that advanced sometime after 5740–5605 yr B.P. The Iceman's burial date coincides with a sharp increase in atmospheric methane and a decrease of δ^{18}O. Starting from about 5000 yr B.P. the methane and δ^{18}O curves diverge, suggesting a trend of increasing humidity and decreasing temperature. These events mark a rapid climatic change that define the beginning of Neoglaciation in the Alps.

(Renland) curves, previously convergent, rapidly diverge, respectively indicating a trend of rising humidity and a lowering temperature. Various paleoenvironmental records, such as glacier expansion (Grove, 1988) and paleobotanical data (Bradley, 1985), document a widespread change during the sixth millennium B.P. For example, in Norway, lithostratigraphic and paleobotanical studies suggest that the Jostedalsbreen ice cap reformed about 5300 yr B.P. (Nesje and Kvamme, 1991); in the eastern and central Alps a marked timberline depression is outlined at about 5000 yr B.P. by Burga (1988). Although several curves of Holocene glacier fluctuations in the Alps have been published (Gamper and Suter, 1982; Röthlisberger, 1986; Leeman and Niessen, 1994), they are often based on indirect evidence (e.g., lake sediments, pollen sequences) or are not closely constrained by calibrated ^{14}C ages; for these reasons, no direct correlation with the Iceman's burial can be clearly established.

As observed in most alpine glaciers (Haeberli, 1995), the recent climatic warming has induced a pronounced reduction in glacier area. At Hauslabjoch, the recent marked increase in glacier shrinkage has dramatically reduced and thinned the glacial cover, particularly in the accumulation zone where ever-larger rock areas are being exposed; this phenomenon is well documented elsewhere in the world (Thompson *et al.*, 1993) and has interrupted the environmental conditions experienced since the end of the ''Holocene Climatic Optimum,'' leading to the discovery of the Iceman. Does it mean that Neoglaciation is ending, as suggested by Luckman (1994)? Are we approaching the highest snowline altitude of the warmest environmental interval reached during the past 10,000 yr? In any case, it is significant that in a very brief time (about 150 yr) alpine glaciers passed from the Neoglacial maximum to the minimal ice extent of the past 5000 yr (Haeberli, 1994).

When air temperatures were 1–2°C higher than today during the warmest part of the Hypsithermal (Nesje and Dahl, 1993; Mannion, 1991), many small glaciers probably disappeared (e.g., in Norway; Nesje and Dahl, 1993). A further increase in temperature of up to 2°C, as predicted by most greenhouse warming scenarios, may lead to a further reduction in glacier-covered area in the Alps amounting to about 25% of today's value, possibly within a few decades (Maisch, 1992). The present situation at Hauslabjoch is the reverse analog of that experienced near the end of the warmest part of the Holocene; if the present trend of global warming continues, further glacier contraction should be expected, we will shortly see the minimum glacier extents of the past 10,000 yr, and climatic conditions will probably approach or exceed those of the warmest part of the Holocene.

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