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Evidence of accelerated englacial warming in the Monte Rosa area, Switzerland/Italy

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Abstract

A range of englacial temperature measurements was acquired in the Monte Rosa area at the border of Switzerland and Italy in the years 1982, 1991, 1994, 1995, 1999, 2000, 2003, 2007 and 2008. While the englacial temperatures revealed no evidence of warming at the firn saddle of Colle Gnifetti at 4452 m a.s.l. between 1982 and 1991, the 1991 to 2000 period showed an increase of 0.05 °C per year at a depth of 20 m. From 2000 to 2008 a further increase of 1.3 °C or (0.16 °C per year) was observed. The measured temperatures give clear evidence of accelerated glacier warming since 1991. The observed increase since 2000 is far beyond a modelled firn temperature increase based on the IPCC climate scenario from 2001. Air temperature records from the Jungfraujoch high-altitude station (MeteoSwiss-Station) from 1980 to 2008 show a mean annual increase of 0.05 °C per year, indicating that the amount of infiltrating and refreezing of meltwater at Colle Gnifetti has increased since 2000. The drill sites on Colle Gnifetti are, however, still located in the recrystallisation-infiltration zone and only marginally affected by meltwater.

A much stronger warming of 6.8 °C was found at locations beneath Colle Gnifetti from 1991 to 2008. This warming is one order of magnitude greater than the atmospheric warming and can be explained only by a strong increase in the latent heat input by infiltrating and refreezing meltwater. The observations indicate that since 1991, an important firn area beneath Colle Gnifetti has already undergone a firn facies change from the recrystallisation-infiltration to the cold infiltration zone due to an increasing supply of surface melt energy.

1 Introduction and motivation

Besides glacier mass balance, firn and ice temperatures of ice bodies can be considered as a key parameter in detecting global warming trends. These temperatures have a sort of a memory function as they register short- and mid-term evolution of the energy balance at the surface. They work as a "natural thermometer with a pronounced long-term memory function". By looking at firn and ice temperature measurements it is possible to assess climate changes in areas where no direct measurements of common climatic parameters are available.

Cold firn and ice in glaciers, ice caps and ice sheets occur when the firn and ice show permanently negative temperatures over the minimum time span of a year. If this is not the case, glaciers are temperate, thus their temperature is at the pressure melting point. Most of the existing cold ice bodies are not cold throughout. These ice bodies are called polythermal (Paterson, 1994). According to the mean annual air temperature (MAAT), different temperature zones of the glacier's accumulation area can be distinguished:

- the recristallisation zone (Shumskii, 1964) or the dry snow zone (Müller, 1962), where the MAAT is so deep that even in summer no surface melt occurs (e.g., Central Antarctica);
- the recristallisation-infiltration zone (Shumskii, 1964) or the percolation zone A (Müller, 1962), where melt only takes place in the uppermost firn layer;
- the cold infiltration zone (Shumskii, 1964) or the percolation zone B (Müller, 1962), where the melt water penetrates through several annual layers of firn; and
- the temperate firn zone, where the melt water warms the firn layers to 0 °C.

Except for the latter zone the above mentioned processes lead to the formation of cold ice in the accumulation area. In addition to the classification above, two different types of cold firn areas can be distinguished. The first type is composed of areas such as summits, crests and very steep slopes, which mainly consists of impermeable ice or very high density firn with many ice layers. The second type contains less inclined slopes or flatter areas with highly permeable firn (Haeberli and Alean, 1985). All of our englacial temperature measurements presented can be assigned to the second type.

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Such cold firn and ice areas will play an important role in sea level rise in the next few decades. In these areas the additional energy input from the atmospheric warming is not transformed directly into increased and accelerated melting but rather into a rise in the firn and ice temperatures. This means that the meltwater amount from glacier melt in high Arctic and high Alpine regions could grow considerably in the next years and decades, when large parts of these areas are becoming temperate (i.e., the firn and ice reaches 0 °C). This phenomenon will not only accelerate the glacier melt of cold or polythermal valley glaciers in mountain chains, it will above all affect the cold and large ice caps and ice sheets in the Arctic and in the Antarctic regions. Existing englacial temperature measurements within the European Alps can be used as an example to demonstrate such effects.

At the end of the 19th century and into the beginning of the 20th century, it was assumed that all glaciers in the Alps are temperate, although Vallot (1893, 1913) had already observed the occurrence of cold firn in the Mont Blanc region at that time. In the 1950s Fisher published several articles about cold firn observations in the Monte Rosa area 1953; 1954; 1955; 1963 as did Haefeli and Brentani (1955) for the Jungfrau area. In the 1970s Lliboutry et al. (1976) and Haeberli (1976) were among the first to systematically investigate the distribution of cold ice and firn in the Alps. In the last 30 years, research activities have increased in the cold high-mountain accumulation areas in the Alps. Many studies have been undertaken in connection with natural hazards and core drillings (Alean et al., 1983; Böhlert, 2005; Darms, 2009; Haeberli and Alean, 1985; Haeberli and Funk, 1985; Laternser, 1992; Lüthi and Funk, 1997, 2000, 2001; Lüthi, 2000; Oeschger et al., 1977; Schwerzmann, 2006; Suter, 1995, 2002; Suter et al., 2001, 2004; Suter and Hoelzle, 2002, 2004; Vincent et al., 1997, 2007a,b).

Such investigations incorporate several related fields of study such as trace element analysis from ice cores, ice flow modelling, mass and energy balance. One additional objective of firn temperature measurements is to monitor and document the influence of the current atmospheric warming on remote high-alpine sites. However, to obtain

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representative measurements, it is necessary to find suitable sites which are not disturbed too much by ice flow, melt and high accumulation rates. Currently there are two sites where such measurements have been repeatedly made: Col du Dôme in the Mont Blanc area (Vincent et al., 2007a,b) and Colle Gnifetti in the Monte Rosa area. Colle Gnifetti is a very wind-exposed firn saddle with accumulation rates of 0.3 to 1.2 m water equivalent per year (Lüthi and Funk, 2000) and the firn-ice transition occurs in a depth of around 40 m (Schotterer et al., 1981).

The shapes and evolution of measured borehole temperature profiles from the recrystallisation-infiltration zone on Colle Gnifetti could be reproduced accurately with a thermomechanically coupled transient heat flow – ice flow model (Lüthi and Funk, 2001). The implementation of such thermal models is made difficult by poorly determined boundary conditions such as large basal heat flux variability (mainly influenced by the complex high mountain topography), horizontal ice/firn advection, changing firn density profiles and the highly variable surface energy balance, which is strongly influenced by the local topography (radiation, wind speed, accumulation, etc.). Many of these influencing factors are site specific. Repeated firn temperature records at selected monitoring sites with suitable glacier geometry are useful for detecting changes in the thermal regime of cold high altitude alpine glaciers. The Swiss Cryospheric Commission of the Swiss Academy of Sciences decided in 2007, based on these findings, to include such firn temperature observations in the existing national glacier observation network. In this study, we bring together all existing englacial temperature data and focus on repeated temperature measurements at different drill sites in the Monte Rosa area at the border of Switzerland and Italy. The following questions will be addressed:

- has there been a significant warming of the englacial temperatures in the Monte Rosa area during the past 30 years?
- can a possible change in the firn facies be detected?
- is there a uniform warming at all sites or is there a strong spatial variability in the warming?

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To answer these questions, unpublished firn and ice temperature measurements from the Monte Rosa area performed between 2003 and 2008 are compared with earlier observations.

2 Methods

2.1 Measuring technique and calibration

The temperature measurements from 2003 to 2008 were performed using negative temperature coefficient (NTC) thermistors, which show a strong change in resistance with temperature and therefore provided a high sensitivity to small temperature fluctuations. The measured resistances were converted into temperatures using an empirical relationship between resistance and temperature, the so-called Steinhart-Hart equation. We used three portable thermistor chains with the total length of chain 1=25 m, chain 2=50 m and chain 3=120 m. The three chains were manufactured in a way to enable if attached in a line, a borehole with a total length of 100 m to be measured. Single chains allow for more flexibility if shorter boreholes are to be measured. The thermistors on the three chains were placed as follows: chain 1 had a feed line of 20 m and the thermistors were at 0.2, 0.4, 0.8, 1.2, 1.6, 2, 2.5, 3, 3.5 and 4 m depth; chain 2 had a feed line of 25 m and the thermistors were at 5, 7, 9, 10, 11, 13, 15, 20, 25 and 30 m depth; and chain 3 had a feed line of 60 m and the thermistors were at 40, 50, 60, 70, 80, 85, 90, 95, 97.5 and 100 m depth. The thermistor type used was YSI-44031. The thermistor chain was manufactured by Stump Bohr AG in Nänikon, Switzerland. The calibration of the thermistors was done in a large cold ice/water basin at 0 °C. According to the manufacturer an accuracy of ±0.2 °C can be expected. The three thermistor chains were connected to a Campbell CR10X data logger and Campbell AM416 multiplexer to make full-bridge measurements on the thermistors. The full-bridge was manufactured by AlpuG AG in Davos, Switzerland. The logger was powered by a 12 V/24 Ah lead battery.

2.2 Locations

A map showing all currently existing measurements sites since the late 1970s is presented in Fig. 1. In 2008, nine borehole temperature measurements sites were performed at three main locations in the Monte Rosa area. The first site was on Colle Gnifetti at altitudes between 4400 and 4500 m a.s.l. with three new and two already existing boreholes (Fig. 2), the second site was close to the Seserjoch at altitudes between 4250 and 4340 m a.s.l., with three new boreholes (Fig. 3) and the third site was on Grenzgletscher at an altitude of around 4250 m a.s.l. with one new borehole (Fig. 3). The new boreholes and some of the existing ones are described in more detail in Table 1.

2.3 Field measurements

Depending on the objective of the measurements (core extraction or only temperature measurements), different drilling techniques were applied to establish the boreholes. Either electrical drill equipment was used to extract ice cores, or steam drilling was applied if the objective was to take measurements of englacial temperatures only. A Heucke steam drill device with a special drill bit and 40 meters of tubing was used to establish the boreholes. With this configuration, boreholes with a diameter of approx. 0.050 to 0.20 m were drilled. The average drilling time for a 25 m deep borehole was around 130 min, varying between 75 and 165 min (Darms, 2009). After the drilling, the thermistor chains were lowered into the boreholes and the logger was connected. The boreholes were always covered with an insulating rubber foam to prevent snow drift and near surface air circulation from penetrating the borehole. Potential air circulation in the borehole itself could lead to an internal heat transport. Experiments have shown that the impact of such a circulation is smaller than the accuracy of the thermistors (Schwerzmann, 2006; Zotikov, 1986). The measurements were done afterwards within 12 to 24 h using a sampling rate of 1 to 5 min. If the measurements were taken directly after the drilling, the latent heat effects produced had to be taken into account

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(Oeschger et al., 1977; Laternser, 1992; Suter, 2002). Thermal adjustment of the thermistors to the surrounding temperature conditions required several days. Therefore, continuous logger readings had to be carried out in order to allow a later extrapolation to calculate the final undisturbed temperatures (Humphrey, 1991).

2.4 Extrapolation procedure

Steam drilling into cold firn or ice disturbs the temperature distribution in the close surroundings of the borehole. Therefore, a certain waiting period has to be allowed for until the temperatures have adjusted to the natural undisturbed conditions. In general it takes a few days for the measurement accuracy 0.1 °C to be reached (Laternser, 1992). To speed up the measurement time, extrapolation of continuous logger measurements directly after the drilling was carried out in order to obtain the final undisturbed temperatures. This procedure was applied at all drill sites except at site B07-1 with a fixed thermistor chain installation, and at B03-1 (B04-1) and B07-2 (B08-4) that had been drilled by an electro-mechanical auger. Thermal adjustment at these sites was assumed to have been completed already. The drilling procedure into cold firn or ice can be considered as an immediate perturbation (energy input) along a linear line (the borehole) (Suter, 2002). The model concept of an instantaneous line source seems to be a good approach in the case of steam drilling. The drilling time is assumed to be infinitely small and the energy input at a certain depth occurs at once. In the case of steam drilling, it is the energy input by the drill bit, whereas additional energy input caused by the insulated drill hose in the course of the drilling is rather small. In a homogenous infinitely expanded medium, the temperature field around a line source can be written as (Carslaw and Jaeger, 1959):

$$\Delta T(r,t) = \frac{Q}{4\pi K} \cdot e^{\left(\frac{-\rho_f c_i r^2}{4Kt}\right)} \quad (1)$$

where $\Delta T(r,t)$ is the temperature difference between disturbed and undisturbed temperature, r is the distance from line source, t is the time since energy input, Q is the energy input per unit length, K is the thermal conductivity of firn, ρ_f=firn density and c_i=specific heat capacity of ice. As only the temperature along a central line of the borehole is of interest, r equals 0 and if $\Delta T(r,t)$ is written as $T(t)-T_f$, the temperature at time t after drilling is (Lachenbruch and Brewer, 1959)

$$T(t)=\frac{Q}{4\pi K}\cdot\frac{1}{t}+T_f \tag{2}$$

where T_f=undisturbed temperature or final temperature. Thus, $T(t)$ is proportional to $\frac{1}{t}$ and the final temperature T_f is the shift on the temperature axis and can be found at $\frac{1}{t}$=0 for $t\rightarrow\infty$. In theory, each depth would have a specific t defining the time which had elapsed since the drill bit reached the corresponding depth. As the drilling time was rather short as compared to the sampling duration and as the measurement was only made several hours after drilling in most cases, the same t was taken for the whole depth range and defined as the time which had elapsed since the end of the drilling and the measurement (Suter, 2002). This method was applied to all new boreholes except to the borehole B08-9, where repeated temperature measurements in the same borehole were computed without using this method, because it was assumed that the thermal adjustment to undisturbed conditions had been completed.

3 Results

Methods and results of temperature measurements performed before 2003 are described in a number of publications (Lüthi and Funk, 2001; Suter, 2002; Suter and Hoelzle, 2002; Haeberli and Funk, 1985; Suter et al., 2001). Presented in this section are englacial temperatures measured in the boreholes drilled in 2003, 2004, 2007 and 2008, and their comparison to the measurements from the earlier studies (Tables 2 and 3). Comparisons are made with temperature measurements at a depth of around 20 m, corresponding to the zero annual amplitude (ZAA), where seasonal fluctuations are less than ±0.1 °C (e.g. see Fig. 5, Tables 2 and 3). Figure 4 contains the measured

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temperatures in the boreholes B08-1 and B08-2 in 2008 compared to the measurements performed in the years 1982 (B82-1), 1991 (B91-A), 1999 (B99-2) and 2000 (B00-A). The comparison shows that the temperatures at a depth of 20 m indicate no change between 1982 and 1991 and have a value of around −14.0 °C. Between 1991 and 1999/2000 a temperature increase of +0.5 °C was measured. Since 2000 the temperatures have increased again by at least +1.3 °C. The nearby borehole B08-1 further downslope already shows a +1.8 °C higher temperature at 20 m depth. This indicates that locations a bit further down the saddle might be affected already by a higher latent heat input due to infiltrating and refreezing meltwater. Figure 5 shows borehole measurements on the northwestern slope of Colle Gnifetti beneath Signalkuppe. At this location a borehole was drilled in 1991 (B91-B) and described by Laternser (1992) and Suter et al. (2001). In 2007 (B07-1), a thermistor chain was installed and remeasured in 2008 (B08-9). At a depth of 20 m, a slight increase in temperature of around +0.4 to +0.5 °C was observed between 1991 and 2007/8. Close to Seserjoch, several boreholes were drilled in 1999 and they are described by Suter (2002). The borehole B99-10 and B08-8 were drilled at the northern slope of Parrotspitze (see Fig. 3). The observed increase at this location is +1.5 °C (Fig. 6). Two boreholes were drilled in 1991 and 1999 by Laternser (1992) and Suter (2002) at the nearby location on Grenzgletscher on a western slope. A very strong increase in temperature was observed between 1991 and 1999. The increase was around +5.5 °C and between 1999 and 2008 +1.3 °C (Fig. 7). On the Seserjoch saddle a borehole was drilled in 1998, measured in 1999 and remeasured in 2008. The observed increase in temperature was +2.4 °C (Fig. 9). Figure 8 presents two measurements B03-1 and B04-1 in a deeper borehole down to 80 m depth close to the bedrock, performed in 2003 and 2004. The temperatures close to the bedrock were around −12.0 °C and in at approx. 20 m depth a temperature of −13.5 °C was observed.

4 Discussion

All the investigated sites in the Monte Rosa area show a clear trend towards higher englacial temperatures since 1991 beyond the accuracy of the measurements. The magnitude of the increase, however, varies significantly between the different sites as an expression of the different amount of available melt energy within the surface energy balance, which determines the amount of infiltrating and refreezing surface meltwater within the firn (Suter et al., 2004). This important processes is supplemented by a general decrease of the thermal conductivity with warmer englacial temperatures (Paterson, 1994). Certain sites such as on Grenzgletscher show a strong increase of +5.5 °C already in the 1991 to 1999 period (see Fig. 7, boreholes B91-D and B99-12). The same is true for certain boreholes at the Seserjoch between 1999/2000 and 2008. Such a strong warming cannot be explained by an increase in air temperatures alone. Figure 10 shows the warming of air temperatures at the high Alpine station of Jungfraujoch at an altitude of 3580 m a.s.l. The measured warming at this site for the whole observation period from 1980 to 2008 is +0.05 °C and therefore lower than the observed warming in the above-mentioned boreholes. Based on these findings, it must be assumed that an important firn area beneath the Colle Gnifetti had already changed after 1991 from a recrystallisation-infiltration to a cold infiltration zone. At the same time the boreholes on the Colle Gnifetti presented in Figs. 4 and 5 show a continuous warming of around +0.5 to +1.8 °C. An overall warming is observed at the borehole B03-1/B04-1 (Fig. 8), where temperature measurements were taken as far down as 80 m depth and where the temperature profile indicates a tendency to warmer temperatures in the uppermost 50 m, a sign of the warming trend of the 20th century.

Whereas the borehole B08-9 only shows a moderate warming as compared to the measurement from 1991, there is a clear trend toward accelerated warming at the saddle point of Colle Gnifetti. The increase of approximately +0.5 °C between 1991 and 2000 reflects the air temperature increase of +0.6 °C observed at Jungfraujoch in the

1990s (Fig. 10). The further increase of +1.3 °C between 2000 and 2008, however, goes beyond the air temperature increase and gives evidence of an increasing meltwater percolation. The Colle Gnifetti sites are thus still situated in the recrystallisation-infiltration zone. However, ongoing warming could lead to a similar situation as on Grenzgletscher and at the Seserjoch saddle, where a facies change was observed after a temperature of around −9 °C was reached at the ZAA . The warming of the englacial temperatures on Colle Gnifetti is stronger at the saddle point than on north-exposed slopes. The opposite is observed on Seserjoch. This is due to the fact that Colle Gnifetti starts only now to be influenced by meltwater. On Seserjoch, meltwater influence began already in the early 1990s (Table 3).

There is a need for further research in this area. Modelling studies in connection with the measurements could lead to better interpretations of the now observed changes (e.g., Lüthi and Funk, 2001; Suter, 2002; Vincent et al., 2007b; Gilbert et al., 2010).

5 Conclusions

The high-altitude firn area of the Monte Rosa has been influenced by a significant warming trend since the beginning of the 1990s. It must be assumed that larger firn areas below the Colle Gnifetti firn saddle have already undergone a firn facies change from a recrystallisation-infiltration to a cold infiltration zone. The englacial temperature evolution at the Colle Gnifetti firn saddle is very significant. Between 2000 and 2008 an accelerated warming trend was observed as compared to the time period from 1991 to 2000. This warming is beyond the observed air temperature increase in high mountain areas of the Alps and gives evidence of the increasing influence of penetrating and refreezing meltwater since 2000. If the warming trend goes on as observed between 2000 and 2008, the increasing meltwater influence could lead to the destruction of this very important old ice archive within a few decades. The englacial warming currently being observed is far beyond the modelled warming at Colle Gnifetti based on IPCC scenarios from 2001 using a one-dimensional time-dependent firn-temperature model including latent heat by refreezing meltwater (Suter, 2002). According to this calculated scenario, the firn temperature already observed would not have been reached until 2020. We would like to mention that such processes may also occur at many sites in high altitude mountain regions in the Arctic or Antarctic, where temperatures are in the same range as on Monte Rosa. Processes leading first to a change from the recrystallisation-infiltration to the cold infiltration facies zone are likely to hide for a longer period an increase in meltwater production and therefore mass loss at these sites. However, as soon as all these areas become temperate, meltwater will be released in large quantities into the water cycle and enhance the already rising sea level. We therefore recommend that temperature profiles be measured at all sites with cold firn areas where in-situ mass balance measurements are performed.

One of the main objectives of this undertaking is to monitor the development of the englacial temperatures at this high altitude site. Therefore, the observations are now included as part of the operational cryospheric measurements in the Swiss Alps by the Cryospheric Commission of the Swiss Academy of Sciences. All borehole data are freely available at the following website: www.cryosphere.ch.

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Table 1. Information about the boreholes drilled in 2003, 2004, 2007 and 2008 with measurement number, date and max. measurement depth, location and altitude of the boreholes, thermistors used and borehole drilling method.

Borehole	Date	Total depth (m)	x (m)	y (m)	Altitude (m a.s.l.)	Thermistor type	Drill type
B82-1	1982	120	633 798	86 576	4450		electro.
B91-A	09 Aug 1991	29	633 820	86 580	4452	Fenwal 197-104QAG-A01	steam
B91-B	26 Oct 1991	28	633 870	86 420	4470	Fenwal 197-104QAG-A01	steam
B91-D	26 Oct 1991	30	633 500	85 900	4250	Fenwal 197-104QAG-A01	steam
B95-1	19 Jul 1996	60	633 922	86 383	4475	Fenwal 197-103LAG-A01	electro.
B99-A	01 Sep 1999	30	633 750	85 765	4293	YSI 44006	steam
B99-2	May 1999	22	633 826	86 595	4454	YSI 44006	steam
B99-8	May 1999	22	633 834	85 808	4306	YSI 44006	steam
B99-10	May 1999	22	633 700	85 620	4330	YSI 44006	steam
B99-12	May 1999	22	633 502	85 911	4250	YSI 44006	steam
B00-A	Aug 2000	25	633 828	86 599	4454	YSI 44006	steam
B03-1	17 Sep 2003	80	633 847	86 524	4454	Fenwal 197-103LAG-A01	electro.
B04-1	15 May 2004	75	633 847	86 524	4454	YSI 44031	electro.
B07-1	03 Nov 2007	35	633 872	86 418	4470	YSI 44031	steam
B07-2	03 Nov 2007	62	634 002	86 554	4452	YSI 44031	electro.
B08-1	24 Aug 2008	26	633 795	86 574	4450	YSI 44031	steam
B08-2	24 Aug 2008	28	633 811	86 586	4452	YSI 44031	steam
B08-3	24 Aug 2008	24	633 918	86 374	4483	YSI 44031	steam
B08-4	25 Aug 2008	59	634 002	86 554	4452	YSI 44031	electro.
B08-5	25 Aug 2008	25	633 500	85 900	4250	YSI 44031	steam
B08-6	26 Aug 2008	24	633 750	85 765	4293	YSI 44031	steam
B08-7	26 Aug 2008	20	633 836	85 802	4306	YSI 44031	steam
B08-8	26 Aug 2008	31	633 686	86 620	4335	YSI 44031	steam
B08-9	26 Aug 2008	35	633 872	86 418	4470	YSI 44031	steam

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Table 2. Information about temperatures measured at 20 m depth for all measurement sites with measurement number, date and depth.

Drill site	Date	Temperature (°C)	Depth (m)
B82-1	1982	−14.1	20
B91-A	02 Aug 1991	−13.9	20
B91B	26 Oct 1991	−13.5	20
B91-D	26 Oct 1991	−9.3	20
B95-1	19 Jul 1995	−13.33	20
B99-A	01 Sep 1999	−9.55	20
B99-2	May 1999	−13.49	20
B99-8	May 1999	−6.79	16
B99-10	May 1999	−13.00	20
B99-12	May 1999	−3.81	20
B00-A	Aug 1999	−13.49	20
B03-1	17 Sep 2003	−13.54	20
B04-1	15 May 2004	−13.50	20
B07-1	03 Nov 2007	−13.11	20
B07-2	03 Nov 2007	−12.99	20
B08-1	24 Aug 2008	−10.38	20
B08-2	24 Aug 2008	−12.18	20
B08-3	24 Aug 2008	−12.37	20
B08-4	25 Aug 2008	−12.87	20
B08-5	25 Aug 2008	−2.52	20
B08-6	26 Aug 2008	−7.15	20
B08-7	26 Aug 2008	−6.40	19
B08-8	26 Aug 2008	−11.52	20
B08-9	27 Aug 2008	−13.14	20

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Table 3. Information about temperatures changes measured at 20 m depth for some selected measurement sites.

Boreholes	Temperature change in 20 m depth (°C)
B82-1 to B08-1	+3.72
B91-A to B08-2	+1.72
B95-1 to B08-3	+0.96
B91-D to B99-12	+5.49
B00-A to B08-2	+1.31
B99-12 to B08-5	+1.29
B99-A to B08-6	+2.40
B99-8 to B08-7	+0.39
B99-10 to B08-8	+1.48
B91-B to B07-1/B08-9	+0.36

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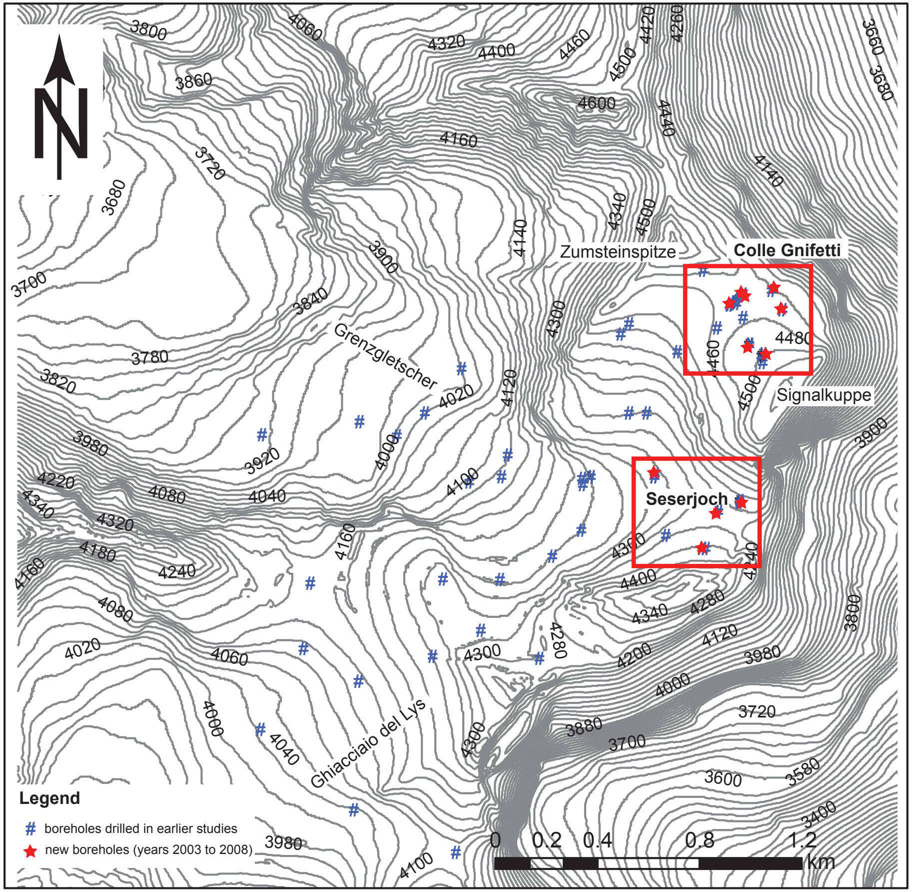

Fig. 1. Location of all borehole sites in the Monte Rosa area. The two insets mark the zoom regions in Figs. 2 and 3.

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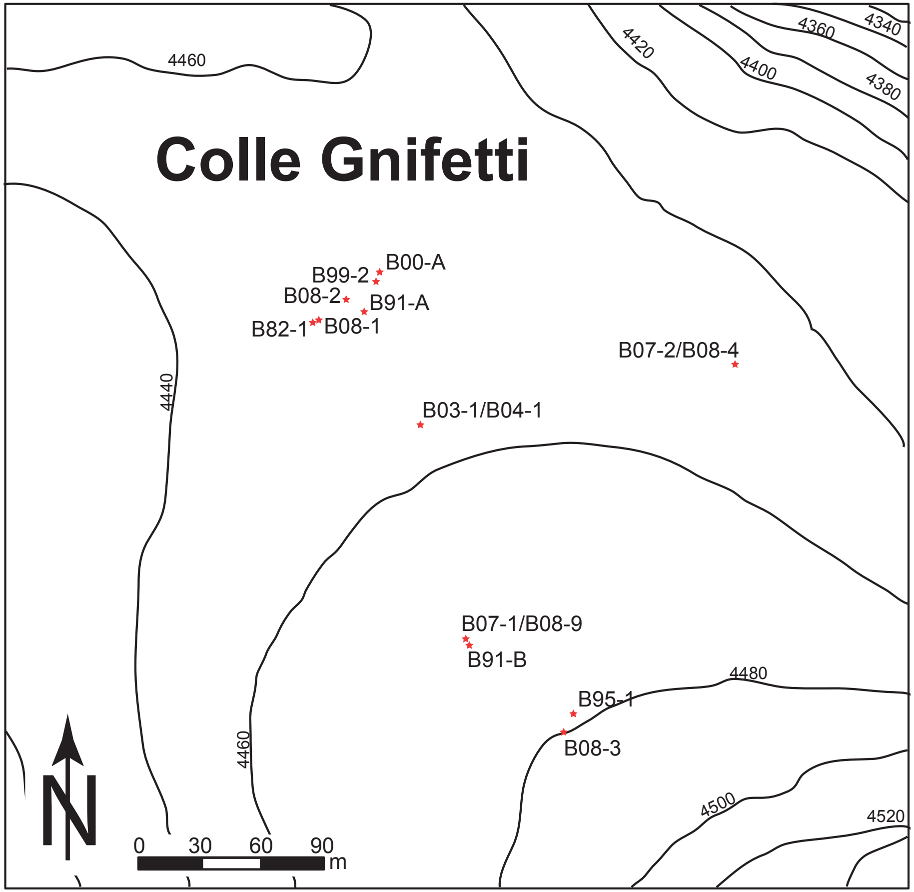

Fig. 2. Location of the borehole sites on Colle Gnifetti.

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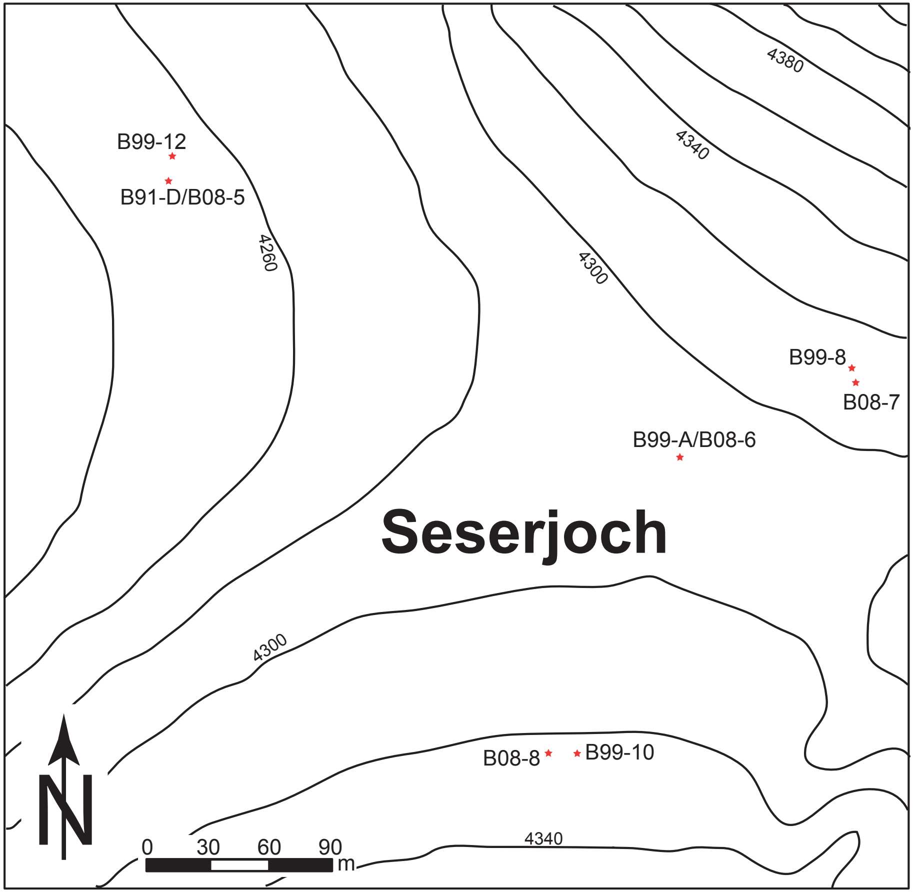

Fig. 3. Location of the borehole sites on Seserjoch.

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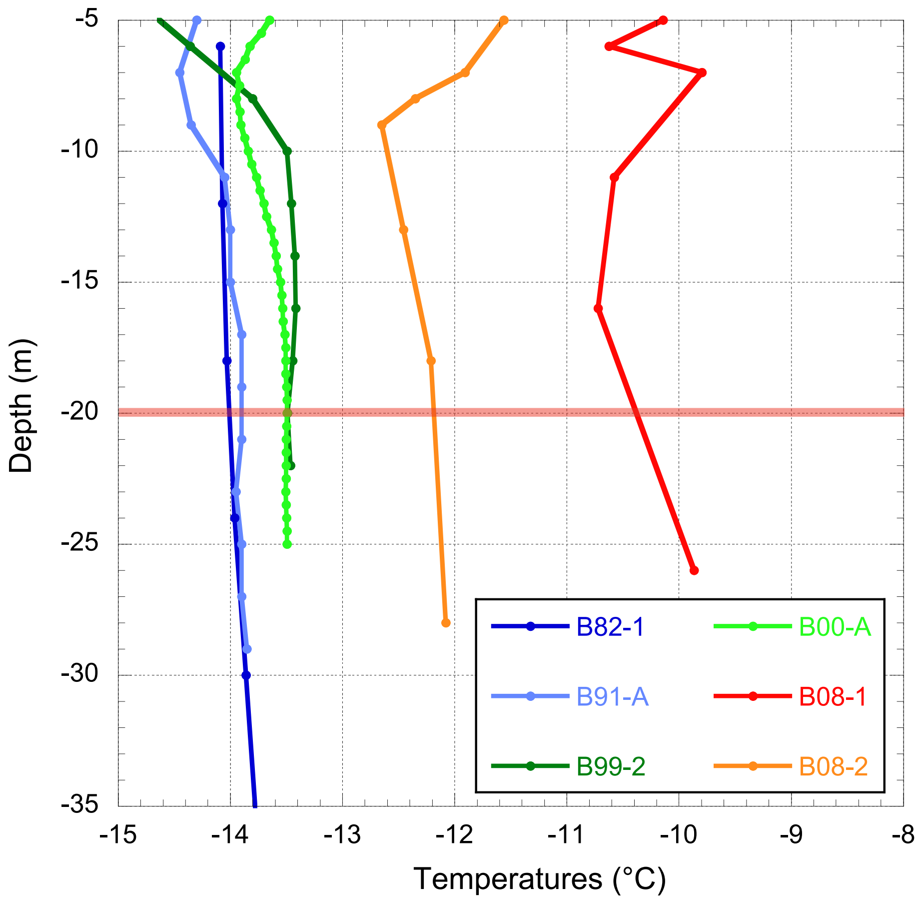

Fig. 4. Temperatures measured in 1982 (Haeberli and Funk, 1991), 1991 (Laternser, 1992), 1999 and 2000 (Suter, 2002) compared with the new measurements at B08-1 and B08-2 at Colle Gnifetti.

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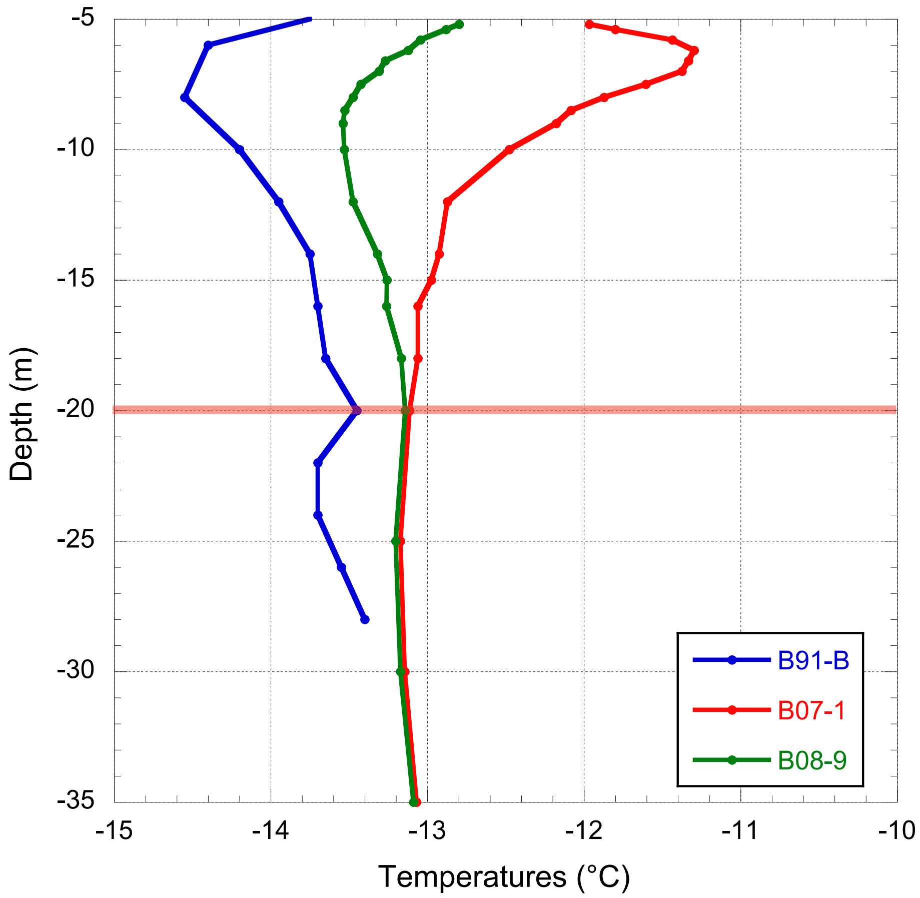

Fig. 5. Temperatures measured in 1991 (Laternser, 1992), compared with the new measurements at B07-1 and B08-9 at Colle Gnifetti.

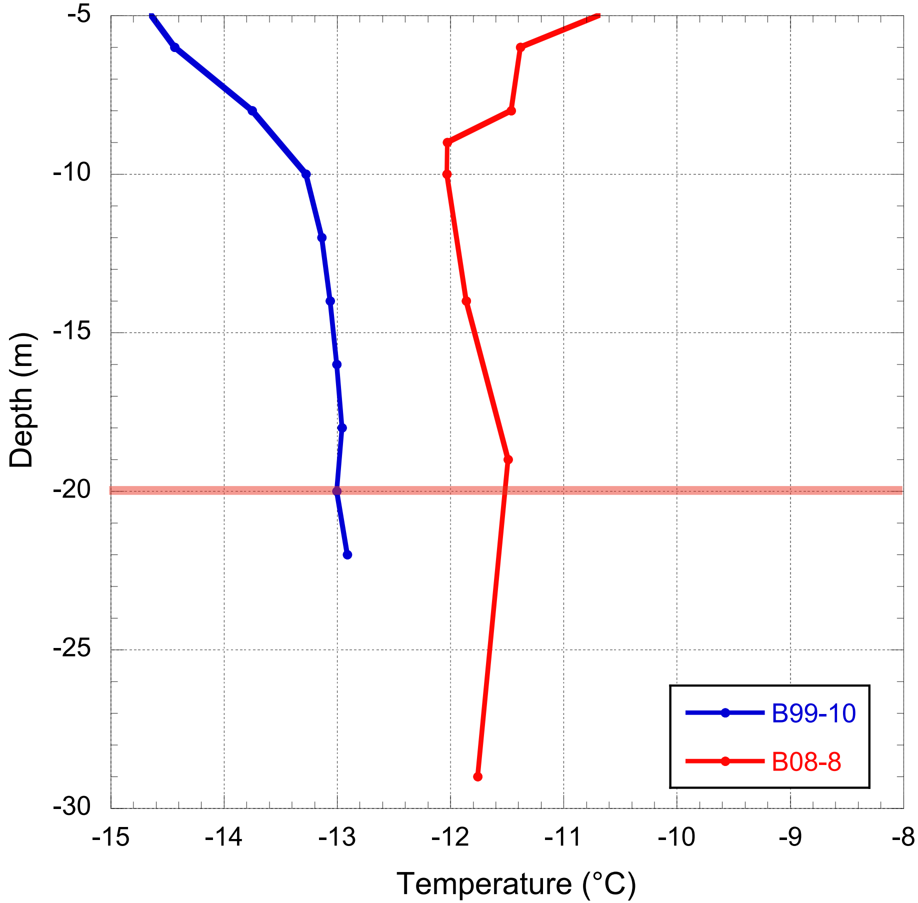

Fig. 6. Temperatures measured in 1999 (Suter, 2000) at Seserjoch, compared with the new measurements at B08-8.

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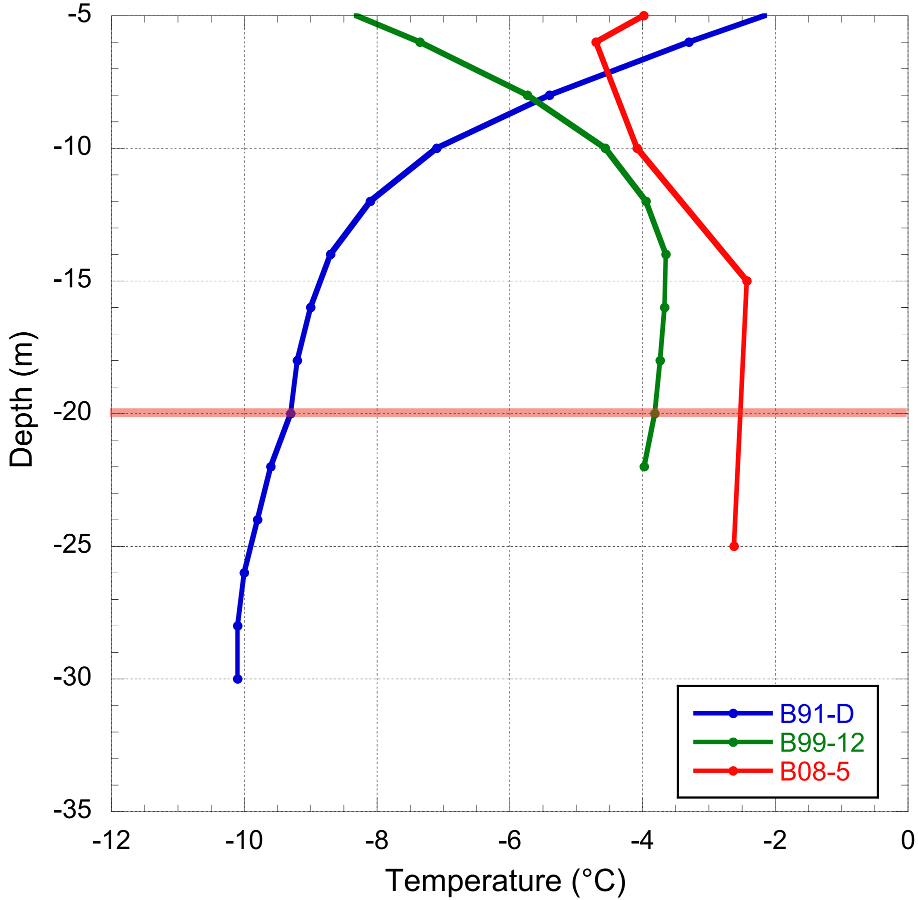

Fig. 7. Temperatures measured in 1991 (Laternser, 1992) and 1999 (Suter, 2000) on Grenzgletscher, compared with the new measurements at B08-5.

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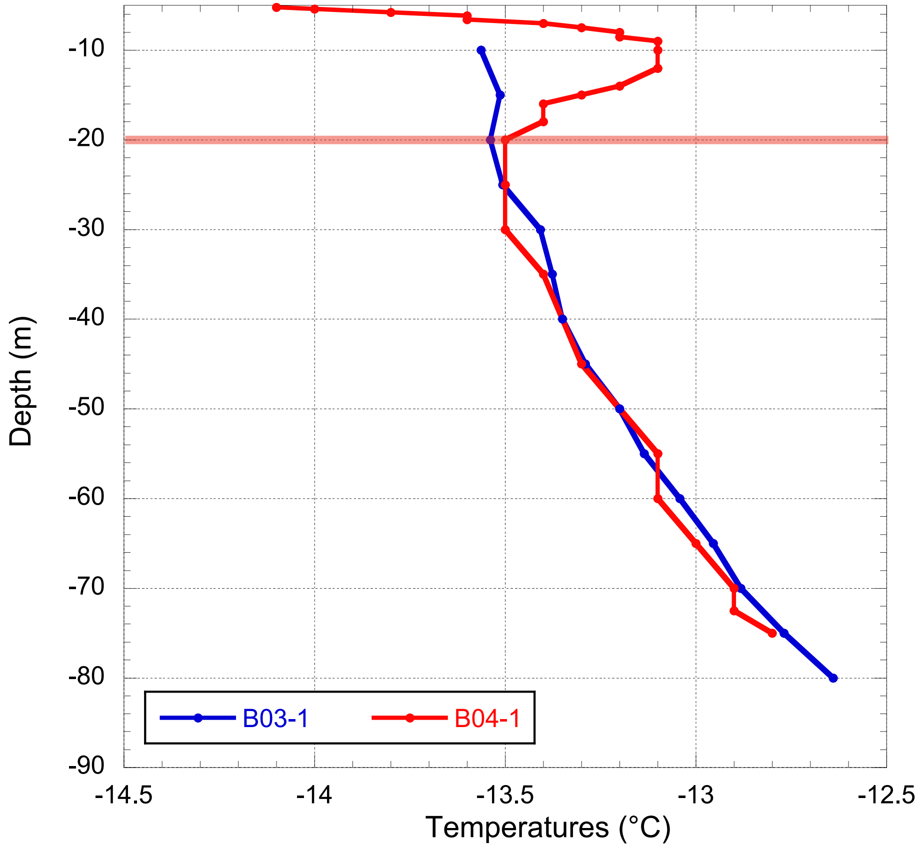

Fig. 8. Temperatures measured in 2003 and 2004 in the B03-1 borehole at Colle Gnifetti.

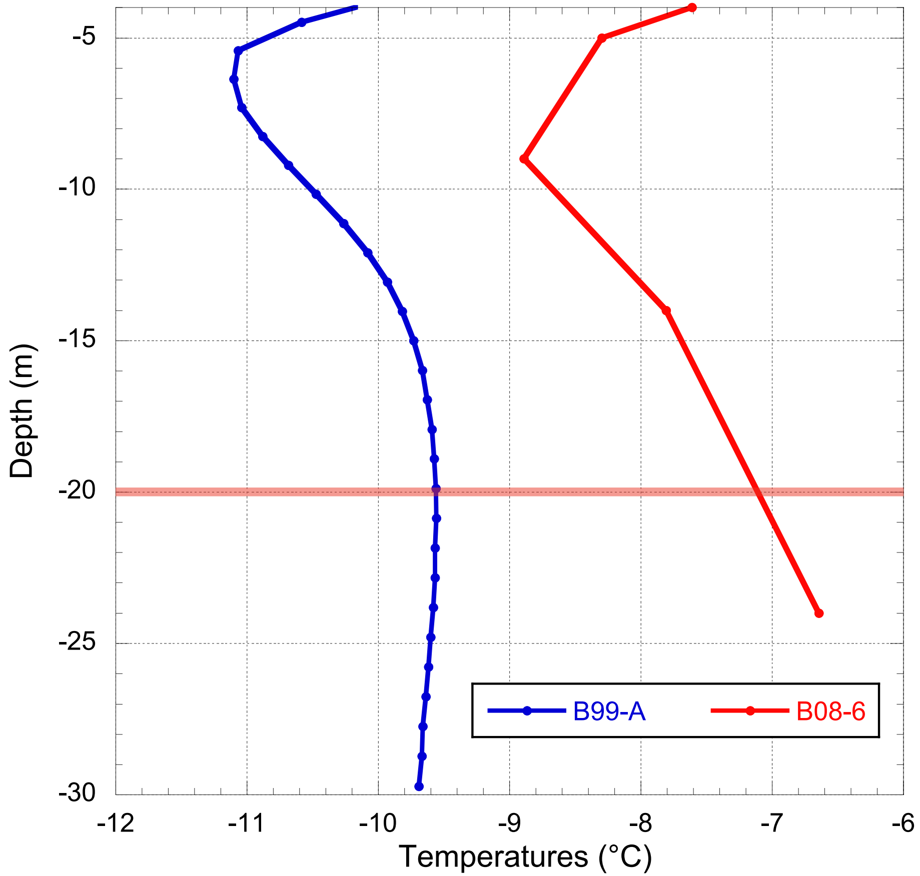

Fig. 9. Temperatures measured in 1999 (Suter, 2000), compared with the new B08-6 measurement at Seserjoch.

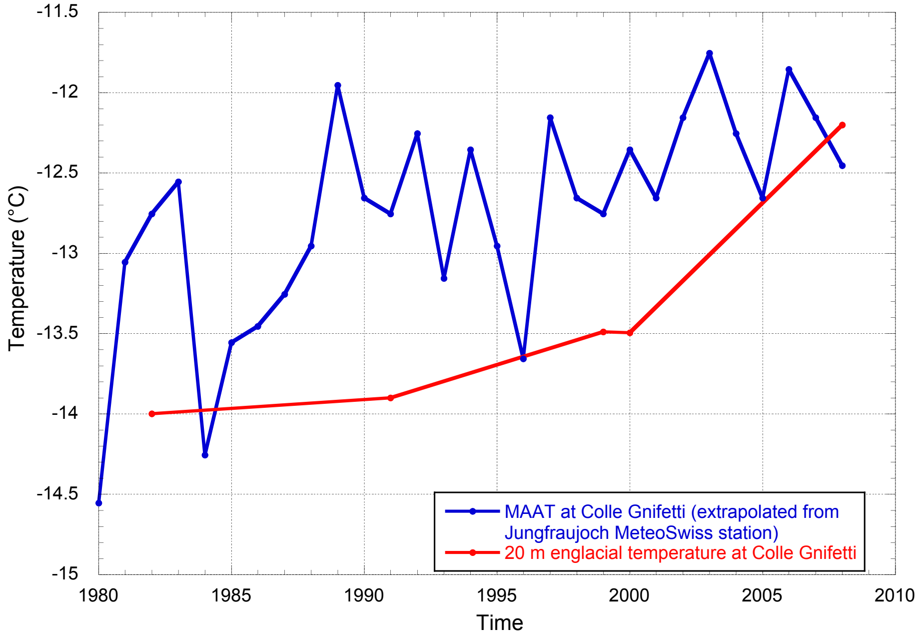

Fig. 10. Measured annual air temperatures at Jungfraujoch extrapolated with a lapse rate of 6.5 °C km^{-1} to the altitude of Colle Gnifetti and firn temperatures at a 20 m depth at Colle Gnifetti.