Climate warming revealed by englacial temperatures at Col du Dôme (4250 m, Mont Blanc area)

Christian Vincent, Emmanuel Le Meur, Delphine Six, Philippe Possenti, Eric Lefebvre, Martin Funk

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Christian Vincent,[1] Emmanuel Le Meur,[1] Delphine Six,[1] Philippe Possenti,[1] Eric Lefebvre,[1] and Martin Funk[2]

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[1] Temperatures were measured in two deep boreholes drilled at the same location in the ice at Col du Dôme (4250 m) in 1994 and 2005, providing clear evidence of atmospheric warming. The 1994 temperature profile was already far from steady state conditions. Results from a heat transfer model reveal that the englacial temperature increase cannot be explained solely by atmospheric temperature rise. The latent heat produced by the refreezing of surface meltwater below the surface also contributes to the englacial temperature increase. Although surface melting is normally very low at this altitude, this contribution became significant after 1980 for temperatures at the top of the borehole. Simulations for different climatic scenarios show that glaciated areas located between 3500 and 4250 m could become temperate in the future. This warming could have a major impact on the stability of hanging glaciers frozen to their beds if the melting point is reached. **Citation:** Vincent, C., E. Le Meur, D. Six, P. Possenti, E. Lefebvre, and M. Funk (2007), Climate warming revealed by englacial temperatures at Col du Dôme (4250 m, Mont Blanc area), *Geophys. Res. Lett.*, *34*, L16502, doi:10.1029/2007GL029933.

1. Introduction

[2] The temperature distribution within cold glaciers is strongly related to the surface energy balance and provides an excellent tool to investigate climate change in very high mountains and in polar regions [*Ritz*, 1989; *Salamatin et al.*, 1998]. Given that the necessary altitude to maintain cold glaciers is higher than 3500 or 4000 m in the Alps, depending on exposition [*Suter*, 2002], the number of study locations is limited. Until now, most deep alpine glacier temperature data have come from investigations carried out at Colle Gnifetti (Monte Rosa, Swiss Alps) between 1982 and 1997 [*Haeberli and Alean*, 1985; *Haeberli and Funk*, 1991; *Lüthi and Funk*, 2001; *Suter et al.*, 2001; *Suter*, 2002]. The 1982 temperature profile measured in a 120-m borehole at Colle Gnifetti exhibits a near steady-state profile with coldest temperatures at the surface. *Haeberli and Funk* [1991] and *Lüthi and Funk* [2001] concluded that no influence of warming since the beginning of the 20th century was discernible. On the other hand, the 1997 temperature profile at Colle Gnifetti shows a temperature inversion in the upper 40 m related to strong atmospheric warming between 1982 and 1997.

[3] Analysis of temperature profiles requires heat flow and ice vertical/horizontal advection modelling. Large uncertainties are introduced by the value of the basal heat flux. The basal temperature gradient is driven directly by the basal heat flux which is strongly influenced by the local topography. Therefore, to compare temperature data from boreholes made at different locations, as was the case for Colle Gnifetti, the spatial variability of the basal heat fluxes must be taken into account [*Lüthi and Funk*, 2001].

[4] Two deep ice borehole temperature profiles were measured in 1994 and in 2005 at Col du Dôme (4250 m, Mont Blanc area). For easier analysis of temperature change, these two boreholes were drilled at the same location. This allows us to remove the effect of basal heat flux variability and reduce the effect of horizontal advection in ice.

2. Measurements

[5] In June 1994, temperature measurements were made in the 140-m deep borehole drilled for the European Alpclim program. From a second borehole drilled in October 2004 for the European Carbosol program, a new vertical temperature profile was obtained for the same location (9 meters apart). Thermistors with 0.05°C accuracy were installed in both boreholes after drilling completion. In 1994, temperatures were obtained 3 days after drilling completion. In 2004, temperatures were measured 5 days after drilling completion, and again 6 months later in the same borehole. Tests repeated in October 2004, January 2005 and April 2005 show that these deep borehole temperatures, measured with different thermistors, were consistent (±0.06°C).

[6] Figure 1a (dots) shows the temperature profiles for 1994 and 2005. The age of the firn or ice is 8, 31 and 100 years old at 40, 90 and 120 m depth respectively [*Vincent et al.*, 1997]. Basal temperature is −11°C for both boreholes and the lower 50 meters of ice do not show any significant change in englacial temperature. On the other hand, a strong warming of firn or ice can be seen in the 90-meter upper part from 1994 to 2005. Moreover, note that the 1994 temperature profile was far from a steady state profile, which would exhibit a sustained cooling from the bottom to the top, apart from the top 15 meters influenced by seasonal variations.

[1]Laboratoire de Glaciologie et de Géophysique de l'Environnement, Centre National de la Recherche Scientifique, Saint Martin d'Hères, France.
[2]Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, Eidgenössische Technische Hochschule Zentrum, Zurich, Switzerland.

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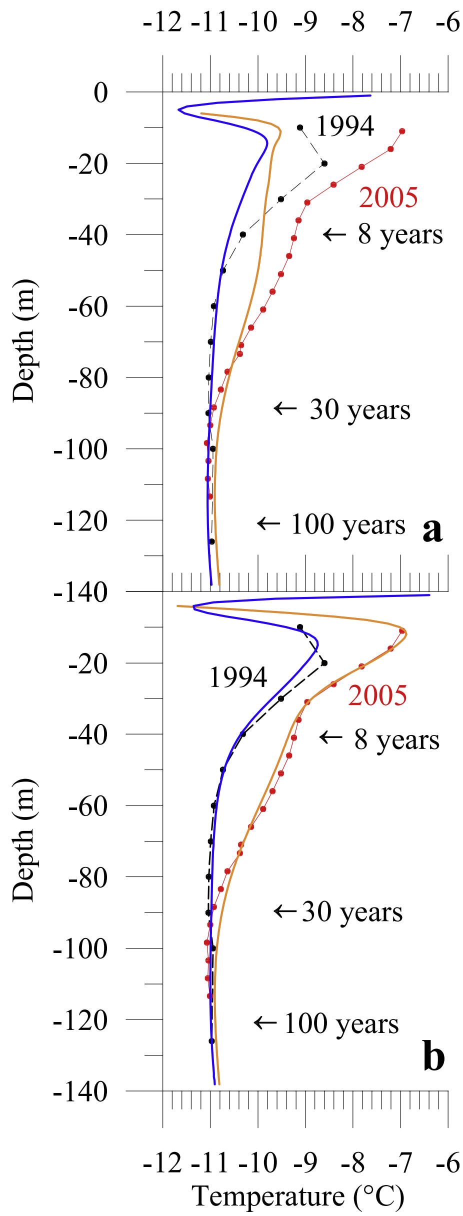

Figure 1. Englacial temperatures measured in boreholes at Col du Dôme du Goûter in 1994 (black dotted) and 2005 (red dotted). Modelled englacial temperatures (a) without taking into account the latent heat flux resulting from surface meltwater refreezing (1994 in blue, 2005 in orange) and (b) taking into account the latent heat flux resulting from refreezing (1994 in blue, 2005 in orange). The initial conditions of modelled temperatures in 2005 are the measured temperatures in 1994. For the 1994 simulation, the initial conditions were set to a steady state profile with −11.9°C at the bottom and −12.8°C at the surface, at the beginning of the 20th century. The age of the ice at certain depths is shown.

[7] Proper heat flow modelling is thus required for a thorough climatic interpretation of these data.

3. Data Analysis Based on Heat Flow Modelling

[8] According to *Malvern* [1969] and *Hutter* [1983], the heat-transfer equation within a cold glacier can be written as follow:

$$\partial T/\partial t = \nabla(k\nabla T) - v\nabla T + Q_f/\rho c_i$$

where T is the firn/ice temperature, k the thermal diffusivity, v the glacier flow velocity vector and Q_f the latent heat released during freezing. Englacial temperatures and their changes are computed at daily intervals using an explicit finite-difference scheme with a one meter horizontal layer thickness (further experiments with 0.5 m and 2 m layer thicknesses gave the same results). Heat production coming from deformation is neglected. At Dôme du Goûter, the glacier is frozen to its bed. Therefore no sliding occurs and the bottom horizontal velocity is zero. As pointed out by *Lüthi and Funk* [2001], one of the main problems related to borehole temperature comparisons lies in the spatial variability of basal heat fluxes encountered in high elevation mountains. As the 1994 and 2005 boreholes were drilled only 9 m apart, the basal heat flux can be considered unchanged. Other difficulties can arise from surface boundary conditions which vary strongly with topography (shading, surface inclination, accumulation). Again, given that the boreholes were drilled at the same location and that the surface horizontal velocity is only 8 m yr^{-1} [*Vincent et al.*, 2007], it can be reasonably assumed that the snow layers in the two boreholes originate from the same area. Thus, the influence of heat flow coming from horizontal advection in ice cannot be responsible for the observed temperature changes between 1994 and 2005. Consequently, these changes are mostly driven by vertical advection in firn/ice, heat conduction and latent heat resulting from surface meltwater refreezing at depth. Vertical advection in ice is derived from the analytical formulation used by *Ritz* [1987], *Vincent et al.* [1997], and *Vincent et al.* [1998], including horizontal flow. However, model studies show almost no sensitivity to the formulation used for vertical advection in firn/ice and a simplified linear relationship gives the same results.

3.1. Recent Change

[9] Figure 1 displays heat flow modelling results relative to June 1994 and April 2005 (continuous lines without dots). Boundary surface temperatures have been obtained using valley meteorological data and a fixed vertical lapse-rate (5.6°C km^{-1}). Meteorological temperatures comes from Lyon (Météo France). Surface accumulation has been inferred from precipitation at Besse using a multiplication factor of 3.0. This factor is deduced from numerous measurements made within the area [*Vincent et al.*, 2007]. Basal heat flux has been set to 15 mW m^{-2}, which leads to a temperature gradient of 0.0067°C m^{-1} close to bedrock. This value is consistent with the observed temperature gradient observed at the borehole bases and with ground heat flux values used in other studies in similar environments [*Lüthi and Funk*, 2001; *Suter*, 2002]. These numerical

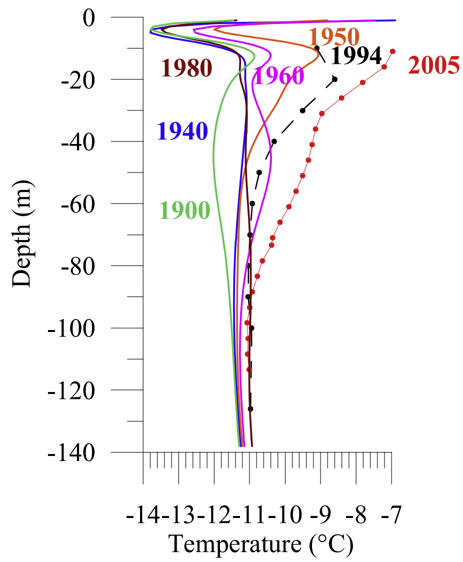

Figure 2. Simulated englacial temperatures in a borehole at Col du Dôme du Goûter over the 20th century. Certain decades have been selected to point out temporal variability over the 20th century.

simulations show that reconstructed temperatures in 2005 cannot match the observed temperatures if the latent heat resulting from surface meltwater refreezing is ignored (Figure 1a, continuous orange line). Given that surface energy balance data are not available, a simple latent heat flux formulation has been included using a degree-day factor (see corresponding results in Figure 1b, continuous orange line). This factor has been calibrated with observations to a value of 1 ± 0.3 mm $°C^{-1}$ day^{-1}. Surface melt occurs when surface air temperature is higher than 0°C. The energy released in the first modelled layer is calculated using the latent heat of refreezing/melting (L_f = 334 000 J kg^{-1}). If the new calculated temperature exceeds 0°C, the temperature is set to 0°C and the excess energy is transferred to the next layer below. Other numerical studies show that when latent heat flux coming from surface meltwater refreezing is ignored, the 2005 profile cannot be reproduced properly whatever the meteorological temperatures used to force the model. This leads to the conclusion that latent heat flux coming from meltwater plays a significant role. However, the latent heat flux formulation using a degree-day factor can be subject to question. To study this, numerical studies were carried out over the 1900–1994 period to make sure that the 1994 profile can be reconstructed with the same degree-day formulation.

3.2. Evolution During the 20th Century

[10] Model studies were carried out back to the beginning of the 20th century. The initial conditions assumed a steady state profile with −11.9°C at the bottom and −12.8°C at the surface. This is consistent with the temperature measured at a depth of 15 meters (−12.8°C) in August 1911 [*Vallot*, 1913]. Using the same latent heat formulation with the same degree-day factor, the 1994 temperature profile can also be satisfactorily reconstructed from 20th century meteorological data (Figure 1b, continuous blue line). Again, the numerical simulations show that reconstructed temperatures in 1994 cannot match the observed temperatures if latent heat resulting from surface meltwater refreezing is ignored (Figure 1a, continuous blue line). Meteorological temperature data coming from Lyon or from homogenised data [*Böhm et al.*, 2001] give very similar results. Further simulations with the same initial conditions fixed at the beginning of the 19th century do not lead to significant changes in the results. We can conclude that introducing 19th century conditions does not influence the present temperature profile. Other numerical experiments were performed to test sensitivity to changes in the snow accumulation rate with time. Over the 20th century, a 20% snow accumulation rate decrease would lead to a 0.6°C temperature rise at the borehole bottom and would have no effect on the 50-m upper part. We can therefore conclude that changes in the accumulation rate over the past 100 years have had no significant affect on the present temperature profile, especially given the small changes observed over the 20th century [*Vincent et al.*, 2007]. Indeed, this study suggests a low decadal variability of snow accumulation and no surface mass balance trend over the 20th century. Furthermore, over such a long time period, we can question the influence of (1) horizontal advection with ice coming from upstream, (2) the variability of basal heat fluxes, and (3) the spatial accumulation variability. Theses influences have been analysed from the horizontal temperature gradient. Comparison with temperatures measured in a borehole at Dôme du Goûter summit, 300 m upstream, reveals a horizontal temperature gradient of 0.007°C/m, i.e. a horizontal heat flux of 15 mW/m^2. This flux is similar to the basal heat flux (with an opposite sign) and influences the temperature itself. However the horizontal heat flux change with time is weak compared to the vertical heat flux change coming from the surface. For instance, the warming of the last two decades leads to a vertical heat flux of more than 100 mW/m^2 in the upper 80 meters of the glacier. Consequently, although horizontal advection in ice is not taken into account, model studies provide an accurate representation of englacial temperature changes over recent decades. Further simulations were therefore conducted to reconstruct englacial temperatures for each decade of the 20th century. In Figure 2, simulation results have been plotted for certain decades in order to show the temporal variability of englacial temperature over the 20th century. For these studies, homogenised temperature data [*Böhm et al.*, 2001] since 1808 were used with the mean precipitation rate at Besse. Between the beginning of the 20th century and 1940, englacial temperatures were very close to a steady state profile. During the forties, englacial temperatures increased to reach values in 1950 similar to those obtained at the beginning of the nineties. This warm event is visible in the 1960 temperature profile, once again with a "bump" at a depth of 50 m. 1980 shows a very near steady state profile preceding the strong warming of recent decades. This result is consistent with observations at Colle Gnifetti in 1982 [*Haeberli and Funk*, 1991; *Lüthi and Funk*, 2001]. Over the 1982–2005 period, the summer mean temperature has increased by 1.1°C compared to the 20th century average. It leads to a temperature profile very far from steady state conditions. The exceptional hot summer in 2003, with summer temperature higher by 4.4°C compared to the

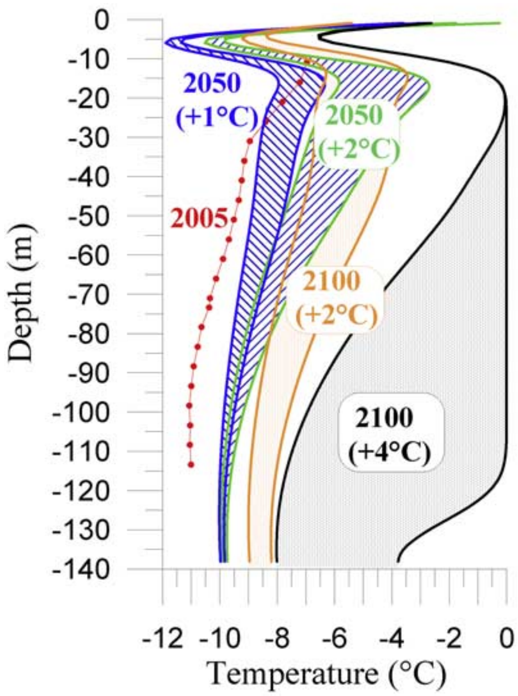

Figure 3. Simulated englacial temperatures for Col du Dôme du Goûter glacier for 2050 and 2100, using the last 20-year average temperature for Lyon and for different scenarios (linear warming of +2°C/century and +4°C/century). The envelopes correspond to uncertainties regarding the influence of the latent heat flux resulting from surface meltwater refreezing.

20th century average explains only a small part of this change.

3.3. Future Changes

[11] Numerical heat flow modelling was used to simulate englacial temperatures in the future for different air-temperature scenarios. Simulations were performed starting with the 2005 temperature profile using the last 20-year average temperature for Lyon and two linear surface temperature increases of 1°C and 2°C until 2050, i.e. 2°C and 4°C up to 2100. The results are shown in Figure 3. The degree-day factor value has been set to 0.7 and 1.3 mm $°C^{-1}$ day^{-1} to cover the maximum range obtained from the previous results. For these scenarios, a moderate basal warming of 1°C is predicted for 2050. The englacial temperature increase is between 0 and 5°C below a depth of 30 m. For the warmest scenario, the upper 30 m of ice becomes temperate in 2100. Moreover, with the highest value of latent heat flux from refreezing surface meltwater, the glacier could be entirely temperate, apart from the bottom 20 meters.

[12] In the Mont Blanc area, temperate firn has been observed between 3500 m and 3800 m depending on exposition and on ice advection from upstream [*Suter*, 2002; *Lliboutry et al.*, 1976]. Thus, following an atmospheric warming of +4°C and a vertical temperature gradient of 0.0056°C/m, this limit should rise to 4210 m for northern expositions. This altitude seems to agree with our results. The lower limit of the dry zone, close to 4200 m during the 20th century [*Lliboutry et al.*, 1976], should climb to 4870 m or more, i.e. higher than the Mont Blanc summit. For this scenario, only a cold infiltration zone could be found in the highest glaciated areas in the Mont Blanc range. Between 3500 m and 4200 m, the ice temperature at the bed could reach the melting point, which would greatly modify the ice dynamics. As a result, the glacier could start to slide over its bed. Therefore this warming could strongly affect the stability of hanging glaciers.

4. Conclusions

[13] A strong englacial temperature rise between 1994 and 2005 has been measured at Col du Dôme and can be attributed to the effect of atmospheric warming. A large part of this rise is due to the latent heat resulting from surface meltwater refreezing. Model studies covering the 20th century show that this contribution is significant after 1980. 1994 and 2005 profiles are very far from steady state profiles. However, bottom borehole temperatures have not yet been affected. In the future, for a scenario of +4°C/century warming, large glaciated areas located between 3500 and 4250 m could become temperate. When the bedrock reaches the pressure melting point, the stability of hanging glaciers will likely be strongly affected. Thorough field investigations and modelling studies relative to surface energy balance are required to accurately assess the temperature evolution of some hanging cold glaciers which could become temperate and therefore unstable.

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M. Funk, Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie, ETH Zentrum, Zürich, Gloriastrasse 37-39, Zürich CH-8092, Switzerland.
E. Lefebvre, E. Le Meur, P. Possenti, D. Six, and C. Vincent, Laboratoire de Glaciologie et de Géophysique de l'Environnement, Centre National de la Recherche Scientifique, 54 rue Molière, BP 96, F-38402 Saint Martin d'Hères, France. (vincent@lgge.obs.ujf-grenoble.fr)