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Calorimetric in-situ determination of ice water content in two Alpine glaciers

Martin P. Lüthi[1], Diego Wasser[1], and Luc Moreau[2]

[1]Department of Geography, University of Zurich, 8057 Zurich, Switzerland
[2]Edytem, CNRS, Université de Savoie, Chambéry, France

Correspondence: Martin P. Lüthi (martin.luethi@geo.uzh.ch)

Abstract. Temperate glacier ice contains liquid water at different concentrations. How much exactly depends on the history of ice formation, the heat supply from dissipative deformation, and on the drainage pathways between ice crystals. The interstitial liquid water content strongly influences the ice viscosity and therefore glacier flow speed. The hydrological system of glaciers is strongly affected by the porosity of the ice matrix. Also, material properties, such as seismic velocities, electromagnetic susceptibility and dielectricity are strongly affected. This renders seismics and radar suitable to measure water content in a glacier. An independent in-situ method is a calorimetric determination by tracking an artificially induced freezing front within the material. Here, we report on two experiments from an artificial cave within a glacier and form a tunnel at the base of a glacier. In both experiments, a liquid water content of 1-2 % was found by analyzing the measured cooling rates with a detailed numerical model of the experimental setup.

1 Introduction

In temperate glacier ice, small amounts of liquid water co-exist with ice crystals as a binary mixture (Harrison, 1972; Nye and Frank, 1973; Mader, 1992). The water contained between ice crystals plays a crucial role for many bulk properties of glacier ice Lliboutry (1976). Numerous experiments have shown that ice deformation is strongly enhanced by an interstitial water content of as little as 0.5 % (Duval, 1977; Adams et al., 2021). A water content of 1 % can lead to a factor five softening of polycrystalline glacier ice. Also the hydraulic permeability is strongly affected by the water-content (Lliboutry, 1996; Fowler and Iverson, 2023), leading to a self-limiting seeping flow of interstitial water. Electromagnetic properties such as the dielectricity of liquid water differ strongly from those of pure ice, such that radar energy is reflected and absorbed, rendering radar an ideal tool to investigate the occurrence of polythermal ice (e.g. Navarro et al., 2005; Murray et al., 2007a; Eisen et al., 2009; Endres et al., 2009). Seismic P-wave speeds and scattering patterns are similarly affected by water (e.g. Gusmeroli et al., 2013). Soluble and insoluble impurities might complicate the picture (Harrison and Raymond, 1976), but will be ignored in this study.

While radar methods are routinely employed to determine the liquid water content in glaciers (e.g. Murray et al., 2000; Gusmeroli et al., 2010; Ryser et al., 2013), the method relies on englacial reference reflectors with known water content, and on material properties that might not be accurate. Only in-situ calorimetric methods can provide a reliable measurement of the interstitial water content, by measuring the heat needed to either thaw or freeze a block of ice. The classical calorimetric

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method involves the use of an adiabatic calorimeter on retrieved ice cores (e.g. Vallon et al., 1976; Duval, 1977) although the de-pressurization of the ice might lead to partial drainage of the water.

The above problem is overcome by in-situ calorimetric measurements, where the water content is determined from the propagation speed of an artificial freezing front and the cooling rate of the freshly frozen ice. This kind of calorimeter implements the Stefan-Problem of a phase-change boundary moving through a material. Hutter et al. (1990) laid out a design to track the speed of the freezing front, and investigated the problem numerically for glaciological applications. Two experiments using a colorimetric cooling setup were performed in an ice tunnel at Findelengletscher (Valais, Switzerland; Zryd, 1991) and in the basal ice of Engabreen (Norway Cohen, 1998). Both experiments suffered from limitations in the setup, where the freezing front could not be easily observed, and both found a water content between 0.7 and 1.5 %.

Here, we report on similar in-situ calorimetric measurements of ice water content in the interior and at the base of two Alpine glaciers, Rhonegletscher and Glacier d'Argentière. The cooling head and temperature probes are directly drilled into the glacier ice. To interpret our measurements, we solve the Stefan problem with a 3D finite element model, properly simulating the detailed geometry of the experiment.

2 Theory

The phase transition by cooling of a fluid initially at the phase change temperature leads to the classical Stefan problem. The quantities controlling the freezing rate are the thermal diffusivity of ice κ, its heat capacity C, the latent heat of freezing L, and the volumetric fraction w of water content within the ice.

The one-dimensional Stefan problem has a analytical small-time solution (Hutter et al., 1990; Gresho and Sani, 2000) for a constant cooling temperature T_c applied at position $r = 0$

$$T(t) = T_c + \frac{T_c}{\mathrm{erf}\xi}\,\mathrm{erf}\frac{r}{2(\kappa t)^{\frac{1}{2}}}\,, \tag{1}$$

where the quantity ξ can be determined from solving the transcendental equation

$$\xi e^{\xi^2}\mathrm{erf}\xi = \frac{CT_c}{wL(\pi)^{\frac{1}{2}}}\,. \tag{2}$$

The position of the freezing front at time t is located at distance

$$r(t) = 2\xi(\kappa t)^{\frac{1}{2}}\,, \tag{3}$$

and the heat flux at $r = 0$ is, with heat conductivity k,

$$Q = k\frac{\partial T}{\partial x} = -\frac{k}{\sqrt{\pi\kappa t}}\,. \tag{4}$$

Equation (1) is only valid for a point source of cooling. In real-world experiments with an finite-size cooling area, this solution is only approximately valid at large distance, such that numerical solutions are required.

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3 Methods

3.1 In-Situ Calorimeter

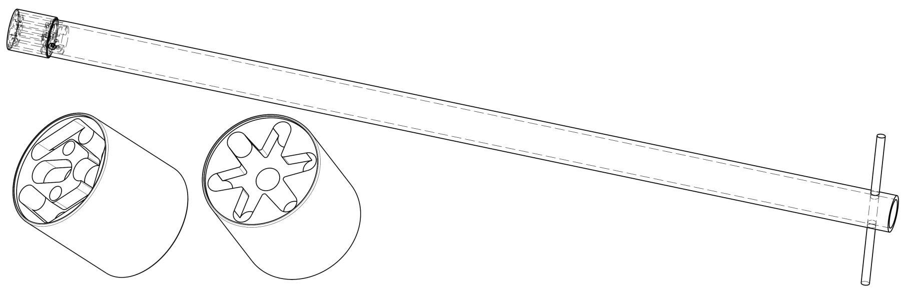

Figure 1. The cooling rod of 50 mm diameter and 1 m length was manufactured from PVC. At the left end, a copper cooling head (inset drawings) was attached which contained a system of channels for the even circulation of the cooling fluid.

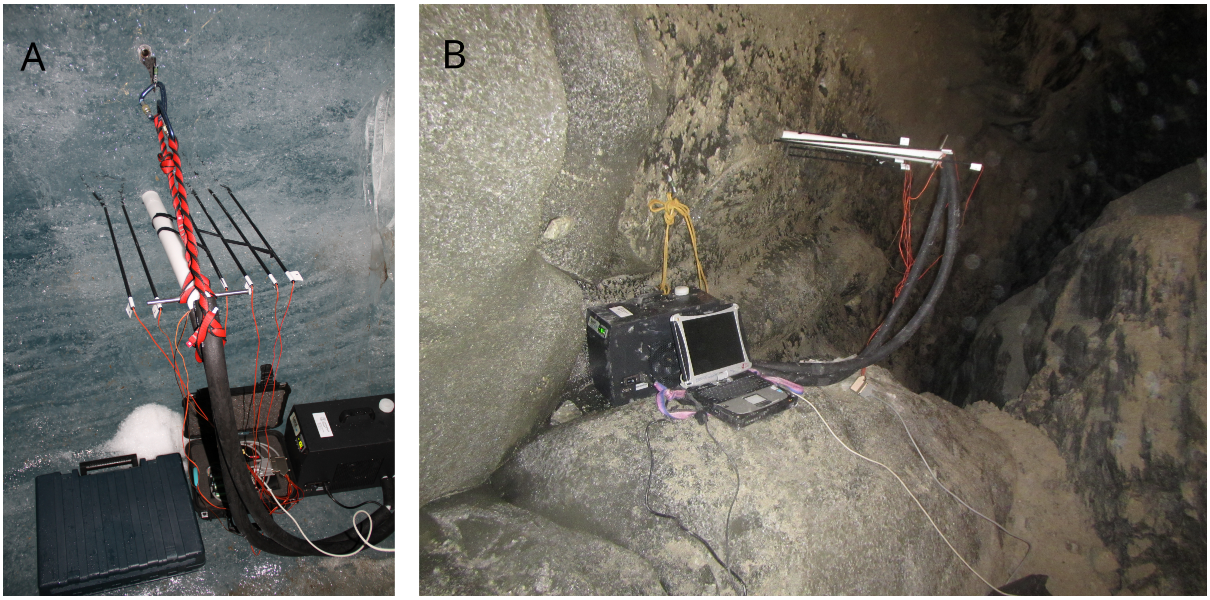

Figure 2. A: Installation of the Cryocalorimeter in the clear ice walls of the Rhonegletscher touristic ice cave. B: Installation of the Cryocalorimeter in the basal ice of the Glacier d' Argentière, accessed from a subglacial tunnel system.

55 For the in-situ measurement of water content within polycrystalline glacier ice we constructed a cooling calorimeter (Cryocooler) that can be readily deployed, and that only requires sustained supply of electric energy. A cooling source is placed within the ice to induce a freezing wave, and temperature sensors are placed at different positions with respect to the cooling source to track the freezing front and the subsequent cooling of the ice.

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The cooling probe shown in Figure 1A consists of a $1000\,\mathrm{mm}$ long PVC pipe of $48\,\mathrm{mm}$ diameter through which two insulated PVC hoses connect to the cooling head. The cooling head of $50\,\mathrm{mm}$ diameter was manufactured from copper, and contains borings to evenly distribute the circulating cooling fluid (insets in Fig. 1), which is necessary to keep the whole cooling head at constant temperature. A circulating fluid (Ethanol) is cooled to a precisely controlled temperature of $-10\,^\circ\mathrm{C}$ or $-20\,^\circ\mathrm{C}$ by a commercial chiller (Laird MRC 150). Insulated rubber hoses (black in Fig. **??**) for the cooling fluid connect the cooling probe to the chiller. The temperature of the cooling head and the drill fluid were measured with temperature probes.

Figure 2 shows the field installation of the Cryocooler at two sites. The cooling probe (white pipe in the image) is installed in a $50\,\mathrm{mm}$ diameter borehole which is readily drilled by a commercial mechanical spiral ice drill (e.g. from Kovacs Inc). To measure the cooling wave, six precision temperature probes were drilled into the ice walls surrounding the cooling probe. The temperature sensors were sealed NTC resistors (YSI 44006RC) attached to the end of fiberglass pipes through which the wires are run. For a precise placement of the probes, a drill guide was used. A spiral drill with 8 mm diameter was used to place the temperature probes at the desired locations. The temperature probe resistivities were measured with a resistive full-bridge with high-precision resistors with small temperature coefficient, and were logged with a Campbell CR1000 data logger in a 10-seconds interval.

All thermistors were calibrated in a regulated calibration bath (Lauda 306) at six temperatures between -10.0 °C and 25 °C, together with a reference temperature sensor, calibrated to an absolute accuracy of 20 mK by the Swiss Federal Office of Metrology. Individual calibration curves were determined for each thermistor, yielding an absolute temperature accuracy of $\pm 50\,\mathrm{mK}$.

3.2 Field Sites

The installation of the Cryocooler system in artificial ice tunnels in two glaciers is shown in Figure 2. The touristic glacier cave at Rhonegletscher (Valais, Switzerland) was excavated every summer, such that the ice walls had been exposed to air for only a few weeks before the measurements on 2017-08-30/31. No flowing water could be observed at the ice wall or during drilling of the boreholes. Several consecutive experiments in different locations of the glacier cave were installed and operated for 5 to 12 hours. The glacier cave of the Rhonegletscher was carved into the clear, bubble-rich marginal ice of $10-30\,\mathrm{m}$ thickness. The installation positions were in the center of the ice column some $10\,\mathrm{m}$ below the glacier surface and $5-20\,\mathrm{m}$ above the glacier bed (depths are rough estimates).

Basal ice could be accessed in the subglacial tunnel system of Glacier d'Argentière (Chamonix, France), which was excavated in bedrock for subglacial water catchments for hydro-power exploitation. The glacier grotto chosen for the installation also hosts the famous bicycle wheel measuring subglacial sliding motion (Vincent and Moreau, 2016). The basal ice accessible in this grotto contained a high concentration of fine sand and silt, rendering the drilling of the boreholes difficult.

3.3 Heat flow model

For a detailed analysis of the evolution of ice temperature, the 3D geometry of the measurement was reconstructed in a finite element mesh. the numerical solution was performed with a heat flow model with phase transition that we implemented within

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the Libmesh finite element library (Kirk et al., 2006). This was accomplished by using an enthalpy scheme (e.g., Aschwanden et al., 2012).

The 3D mesh was generated with a custom script that uses the finite element mesh evaluation library FEVAL (Fig. 3). The mesh consisted of 43000 Hex8 elements with linear Galerkin weighting. The initial ice temperature was set to $0\,^{\circ}\mathrm{C}$ throughout the domain. Dirichlet boundary conditions for temperature were enforced with a penalty method to a time-dependent $T_c(t)$ at the location of the cooling head. No other boundary conditions were enforced.

The model simulations were either conducted with a constant cooling temperature T_c, or were driven with the temperature history measured within the cooling head. The modeled temperature was extracted at the required positions within the model domain by interpolation of the numerical solution with the finite element shape functions.

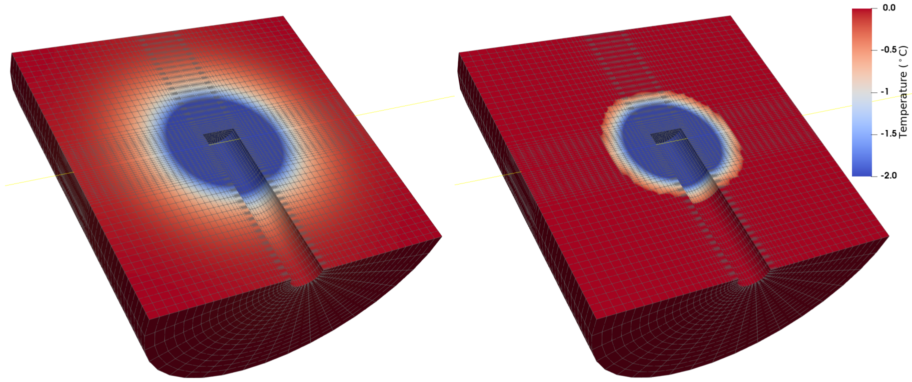

Figure 3. Top: Finite element model of the ice surrounding the cooling rod after after $1800\,\mathrm{s}$. Blue colors show the cooling temperature of -$10\,^{\circ}\mathrm{C}$ and the frozen ice surrounding the cooling head. Water content strongly affects the localization of the cooling front: (a) for no water ($w = 0$) the temperature transition is smooth (b) for a small water content ($w = 2\,\%$) a clearly localized cooling front is discernible, outside of which the temperature stays at exactly $0\,^{\circ}\mathrm{C}$.

4 Results

4.1 Rhonegletscher

Four experiments were conducted in different locations in the glacier cave under Rhonegletscher. Here, we analyze only on the final one (re4), as the others served for testing the instrument setup, or contained interruptions of the cooler system. Results from all four experiments are shown in the Appendix.

The thermistors at $5\,\mathrm{cm}$ distance from the cooling head reached sub-freezing temperatures after ca. 30 minutes, the ones at $10\,\mathrm{cm}$ distance after 1 hour. The temperature sensors at the same nominal distance from both sides of the cooling head show a different behavior. One reason was the difficulty to drill precisely parallel to the cooling rod to place the temperature sensors. Their approximate real location was determined in the field, and modeled temperatures were extracted from the model results at

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these exact positions. Inhomogeneities, air bubbles and the size of ice crystals are further complications that will be discussed later.

Figure 4 shows that the modeled onset of freezing at the three distances matches reasonably well for a liquid water content of $w = 1\,\%$. In contrast, the subsequent cooling of the ice agrees better for $w = 2\,\%$.

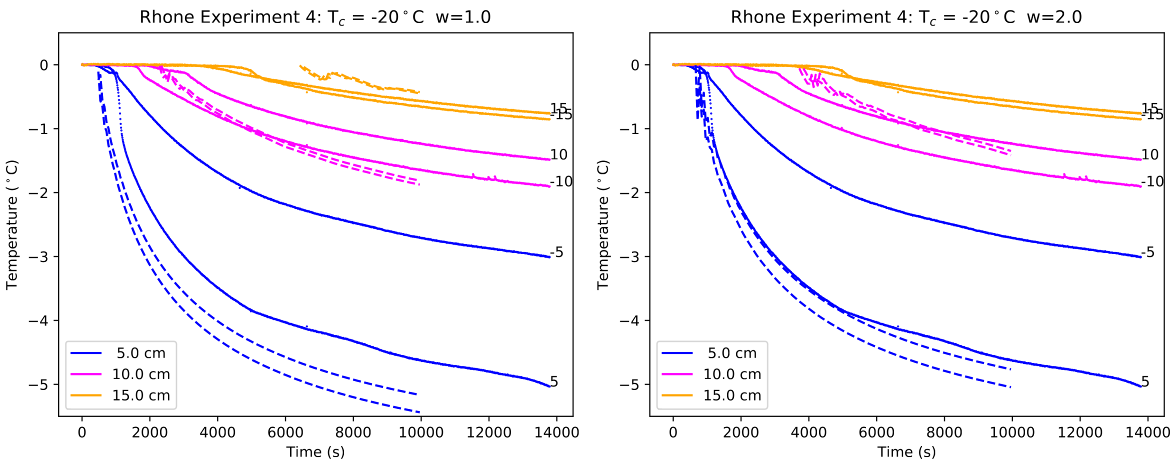

Figure 4. The measurements from Rhonegletscher experiment 4 (re4). The experiment was running for 3.75 hours at the nominal cooling temperature of -20 °C. Measured ice temperature at different distances to the cooling rod are shown with solid lines. Dashed lines show the results from the numerical model runs. A: model results for a water content of 1 % B: model results for a water content of 2 %.

4.2 Glacier d'Argentière

Two cooling experiments were conducted in the basal ice accessible through the rock tunnel system at Glacier d'Argentière. The basal ice accessible at the site contained large amounts of sand and silt, which rendered the proper placement of the cooling rod and the thermistors difficult. Only the results of the second experiment (ae2) with a satisfactory setting of the probes are analyzed here. The cooling curves and the corresponding model interpretations are displayed in Figure 5.

A good agreement between modeled and measured cooling curves is obtained for a liquid water content of 2 %. A lower water content yields a better timing for the onset of freezing at 10 cm distance, but also a less convincing evolution of the ice temperature. Water contents exceeding 2 % can be ruled out, as the modeled cooling curves do not agree with measurements.

5 Discussion

The two experiments reported here showed a liquid water content of the glacier ice between 1 and 2 %. These values fall within the range of water contents reported in the literature (Tab. 1 in Pettersson et al. (2004)). The (indirect) determination at Sermeq Kujalleq (Jakobshavn Isbræ, Greenland Ice Sheet) indicated a likely value of 1.5 % at the CTS (Lüthi et al., 2002), which would agree with our measurements of the basal ice at Glacier d'Argentière.

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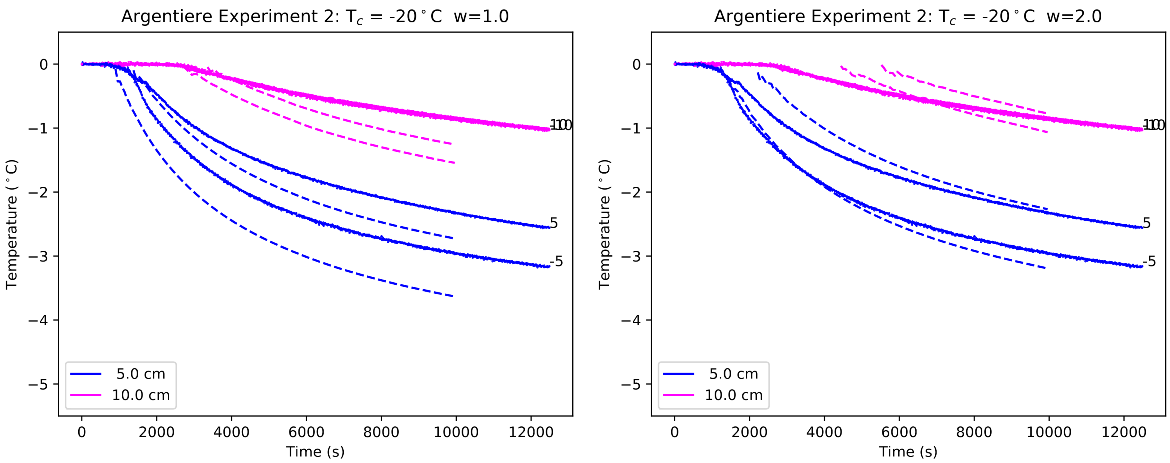

Figure 5. The measurements from Glacier d'Argentière experiment 2 (ae2). The experiment was running for 3.5 hours at a nominal cooling temperature of -20 °C. Measured ice temperature at different distances to the cooling rod are shown with solid lines. Dashed lines show the results from the numerical model runs. A: model results for a water content of 1 % B: model results for a water content of 2 %.

Interestingly, earlier in-situ calorimetric determinations obtain a water content between 0.6 and 1.5 % (Duval, 1977; Cohen, 1998; Zryd, 1991; Pettersson et al., 2004). Our higher values might be due to the position of the sampling locations close to the bedrock.

The temperature evolution at sensors with at the same nominal distance from the cooling head differ considerably in our experiments, especially for small distances. Obviously, inhomogeneities in the polycrystalline ice can largely influence the spreading of the cooling wave. Ice crystal sizes in vicinity of the boreholes were between 2 and 10 cm, such that large differences in the cooling rates should be expected in close vicinity of the cooling head. The results at the larger distance of 15 cm are very similar, since the an equal distribution of the number of water inclusions is more likely in a larger probed volume of ice. Bands of air bubbles form another important and anisotropic inhomogeneity, especially in Rhonegletscher, that cannot be accounted for in a numerical model without a detailed mapping of the crystal structure.

The interpretation of the measurements with the numerical model exhibits a recurring pattern: the time of freezing is compatible with 1 % of water, whereas the cooling curves agree better for a higher water content up to 2 %. This might hint to a different thermal diffusivity of ice than the one assumed in the model runs. With a lower ice-water diffusivity (i.e. at a higher water content) the shapes of the cooling curves are better captured, at the expense of a wrong timing of the freezing of the sensors that are further away from the cooling probe. Numerical tests with different diffusivities were performed, although without any significantly better matching of the cooling curves.

It seems likely that water contents of the ice exceeding 2 % cannot be sustained under drained conditions Lliboutry (1996), as were encountered in our experiments. By necessity we drilled in ice walls exposed to ambient air pressure, even under 100 m such at Glacier d'Argentière. This means that our observations do not exclude the possibility of a considerably higher water content under high ambient pressure, and in undrained conditions, as would be encountered at depth in glaciers or ice sheets.

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Such higher water contents have been inferred from the analysis of radar soundings (e.g. Murray et al., 2007b; Gusmeroli et al., 2010; Ryser et al., 2013).

Conclusive experiments with a calorimetric experiment under undisturbed ambient conditions at depth would yield the important information, whether interstitial water contents exceeding 2 % are possible under glaciers. A high water content of the basal ice would lead to very high ice deformation rates in the area where shearing stresses are hightest. Such very soft basal layers with high deformation rates have been observed in boreholes at the base of the Greenland ice sheet (Lüthi et al., 2002; Ryser et al., 2014), as well as Alpine glaciers (Roldán-Blasco et al., 2025).

6 Conclusions

By in-situ measurements within the Rhonegletscher glacier cave, and in the basal ice under Glacier d'Argentière, we measured the liquid water content with a colorimetric system by tracking the freezing front and the subsequent cooling of the ice surrounding the cooling head. At both sites a liquid water content between 1 and 2 % was determined by comparing the measurements with the results from a numerical heat flow model. These values are at the upper end of calorimetric determinations of the water fraction in polycrystalline glacier ice, and might be due to their position close to the bedrock.

Code and data availability. The field measurements and the code to interpret the data are accessible at Zenodo.

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Appendix A: Comparison with analytical solutions

Model results for a point source were compared to the analytical solution for a spherical geometry (Hutter et al., 1990; Carslaw and Jaeger, 1959). The agreement is excellent.

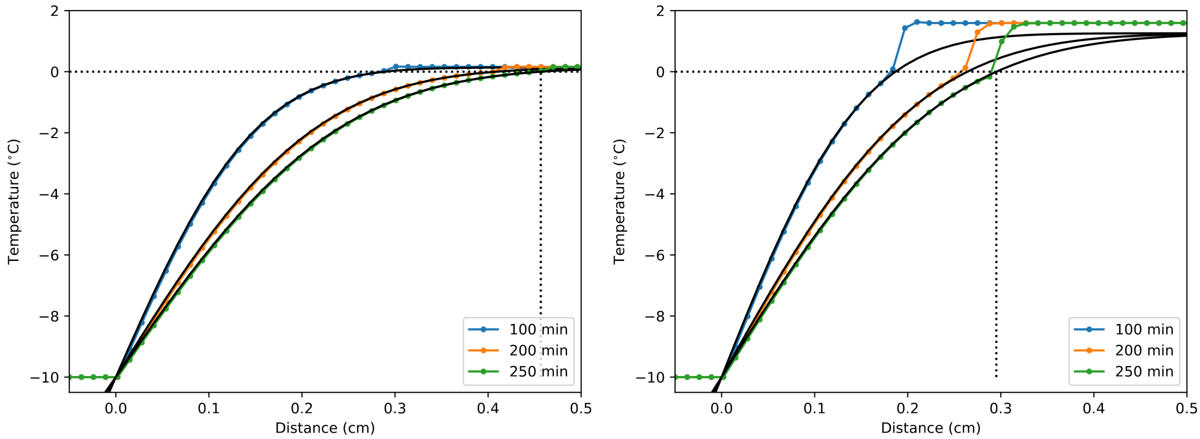

Figure A1. Comparison of model results for a point source with the analytical solution for a spherical geometry.

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Appendix B: Measurements at Rhonegletscher

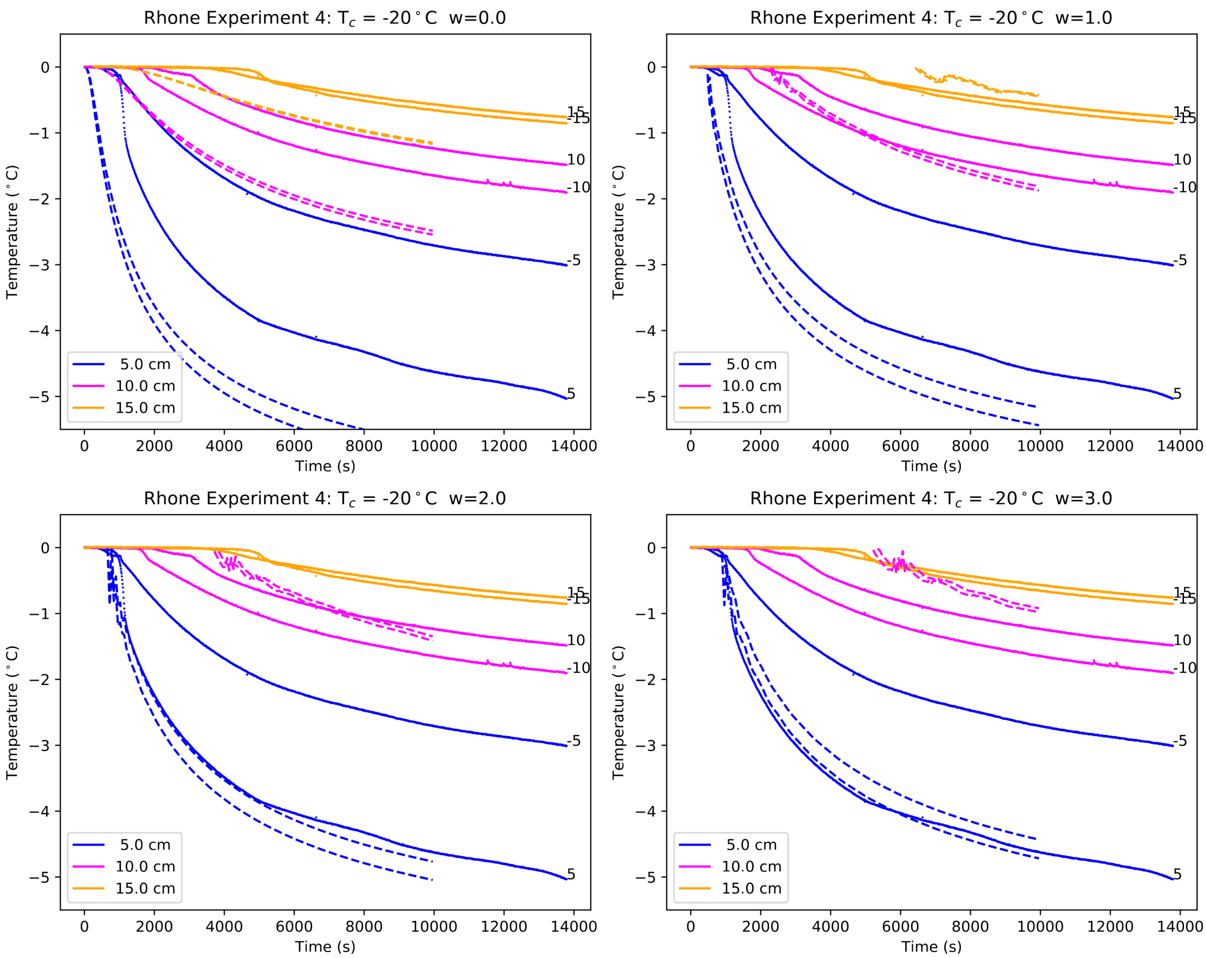

Figure B1. The measurements of experiment re4 on Rhonegletscher compared to model simulations for water contents of 0, 1, 2, and 3 %.

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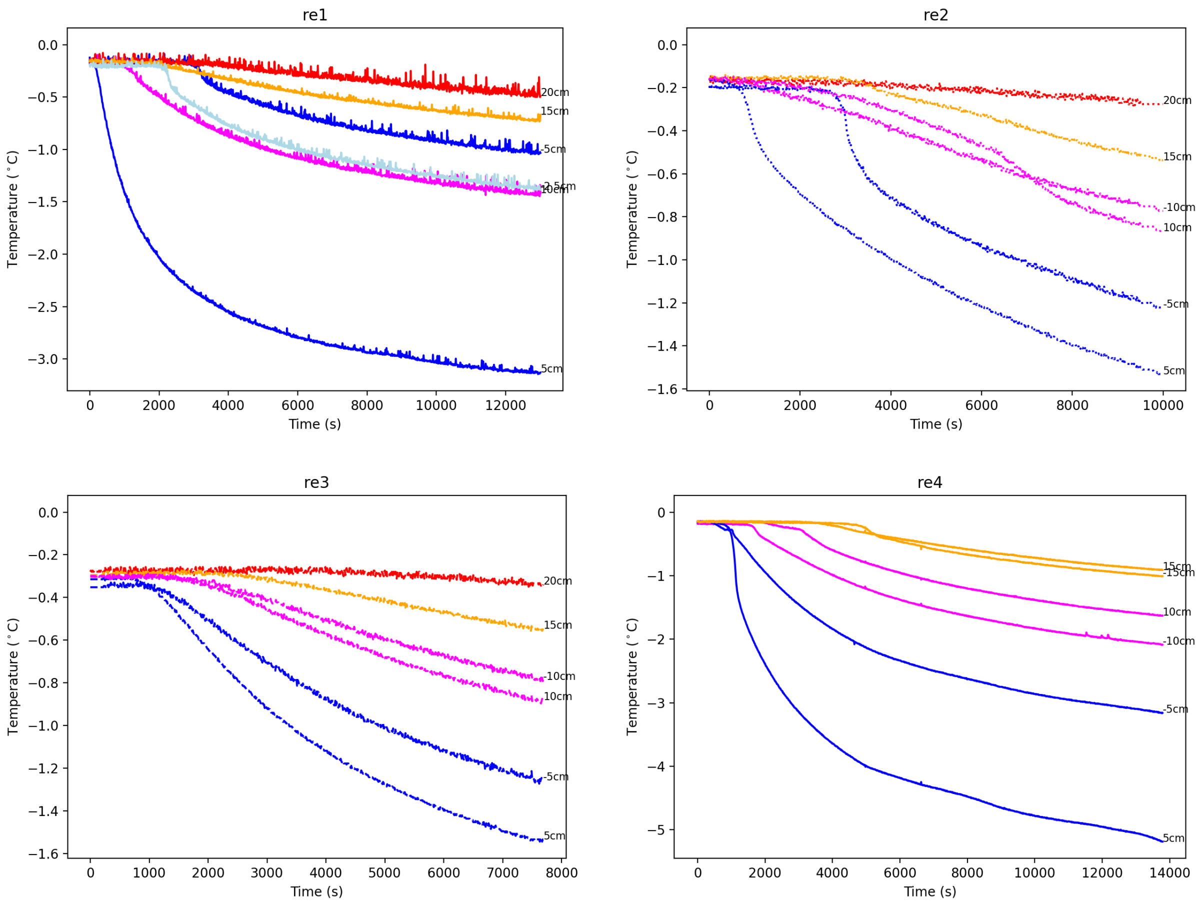

Figure B2. All cooling experiments from Rhonegletscher. Note that the cooling temperature and the experiment duration were different for each experiment.

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165 ## Appendix C: Measurements at Glacier d'Argentière

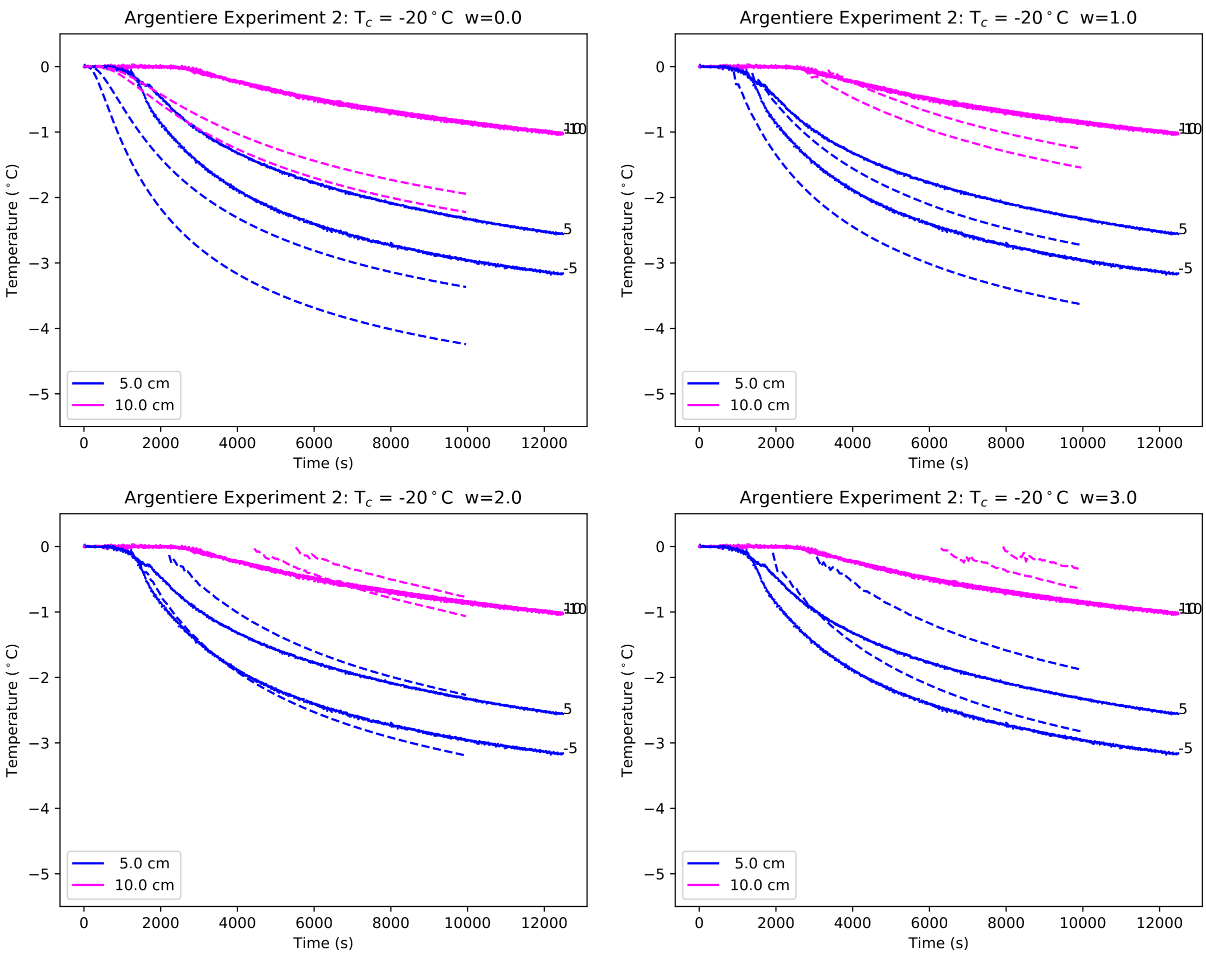

Figure C1. The measurements of experiment ae2 on Glacier d'Argentière compared to model simulations for water contents of 0, 1, 2, and 3 %.

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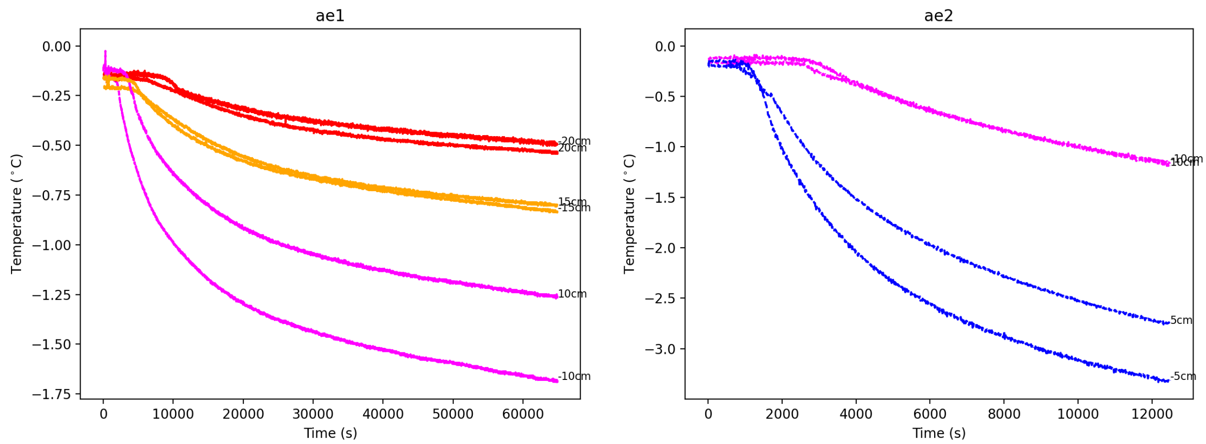

Figure C2. All cooling experiments from Glacier d'Argentière. Note that the cooling temperature and the experiment duration were different for each experiment.

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Author contributions. MPL designed the study, performed the field experiments, wrote the analysis codes and wrote the manuscript. DW built the field equipment and performed the field experiments. LM provided access to the Glacier d'Argentière site and performed the measurements. All authors commented on the manuscript.

Competing interests. We declare no competing interests.

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