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In-situ measurements and temporal evolution of the thermal conductivity profile of an alpine snowpack

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ABSTRACT:

We report on a 3-months long time series of *in-situ* measurements of the thermal conductivity (k_T) of snow at 6 fixed heights in an alpine snowpack in the Mont-Blanc mountain range, France, at an altitude of 2400 m. Automatic measurements were carried out every two days using the heated-needle probe technique. Results show consistent patterns of thermal conductivity increase throughout the measurements campaign. The temporal rate of change of k_T varies up to 0.01 W m^{-1} K^{-1} d^{-1}, with maximum values just after snowfall. A cursory comparison of the measured k_T values with the prediction of the snowpack model CROCUS shows that at first order the model performs rather satisfactorily. However, a quantitative understanding of the variations of k_T over time would require an in-depth assessment of physical processes occurring during snow metamorphism.

KEYWORDS: thermal conductivity, snow, heated-needle probe, CROCUS snowpack model.

1 INTRODUCTION

The thermal conductivity of snow (k_T) is an important variable describing the physical properties of the snowpack. It determines the rate of heat transfer at the Earth surface in snow-covered regions, and its vertical profile governs temperature gradients, which in turn drive snow metamorphism, i.e. the modification of the structure and physical properties of the snowpack. There is therefore a feedback loop between snow thermal conductivity and metamorphism (Domine et al., 2007).

Models that are used to predict the physical properties of the snowpack over the winter season rely on empirical to semi-empirical methods to estimate the vertical profile of k_T. For example, the CROCUS model (Brun et al., 1989, 1992) uses an empirical relationship between k_T and the snow density (Yen, 1981). Several other such parameterizations have been proposed (see Sturm et al., 1997, for a review). The SNOWPACK model (Lehning et al., 2002) uses a more sophisticated approach for estimating k_T, based, among other variables, on the mean bond size between snow grains.

Measuring k_T in a snow sample can be done in various ways. The theoretically most straightforward method requires the simultaneous measurement of the heat flux (**F**) and the temperature gradient (∇T). k_T is given by:

$$k_T = |\mathbf{F}| / |\nabla \mathbf{T}|$$

Such a method has been successfully used in the laboratory (e.g. Schneebeli and Sokratov, 2004), but it is rather impractical in the field. The alternative option for field determinations of k_T is to use the so-called « heated-needle probe » technique (see e.g. Sturm et al., 1997). The main drawbacks of both approaches is that they only allow to calculate the « effective thermal conductivity » of snow, that includes latent heat fluxes associated with water vapor movements, and not « thermal conductivity » *stricto sensu* (Arons and Colbeck, 1995). In what follows, we refer to «k_T» although it must be recognized that this represents effective thermal conductivity. In addition, such methods cannot be reliably used in anisotropic media, which sometimes happens to be the case for some snow layers (e.g. columnar depth hoar).

At present, several scientific gaps persist in the description and the modeling of the thermal properties of snow. The critical one is the field validation of the model predictions of k_T. Ongoing efforts include better field assessments of the vertical profile of the thermal conductivity of snow and its temporal evolution. To progress on these issues, during the field season 2008-2009 we deployed a vertical array of six heated-needle thermal conductivity probes, which were progressively embedded in the snowpack. We present below the first data from this field campaign. A preliminary comparison is made with the output of the snow-cover model CROCUS, in terms of k_T.

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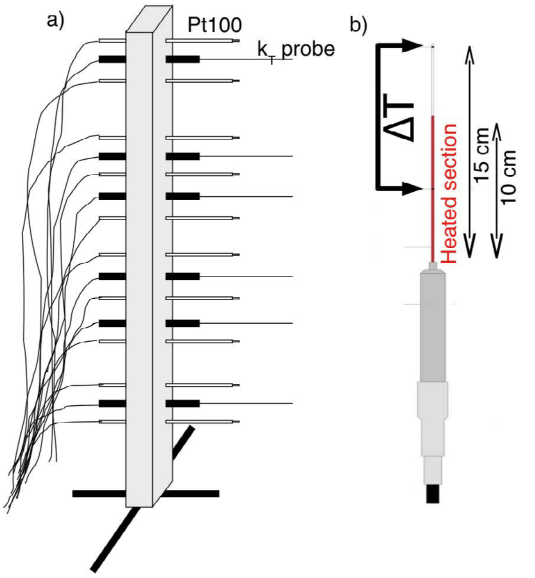

Figure 1: a) Overview of the analytical setup used for temperature/k_T measurements in the snowpack. The height of the mast is 2m. b) Detailed view of a k_T probe, illustrating where ΔT is measured.

2 EXPERIMENTAL

2.1 Experimental setup

Figure 1 shows the design of the field experiment carried out from January 15 to April 8 2009, on the right bank moraine of the *Argentière Glacier* (Chamonix, France) at an altitude of ca. 2400 m. The chosen site features a meteorological station used for long-term glacier mass-balance studies. Long- and short-wave incoming radiation are measured in addition to standard meteorological variables (temperature, RH, wind speed and direction). Snow height was additionally continuously measured during the field experiment. k_T measurements were performed at 6 heights in the snow using heated-needle probes (68, 88, 98, 118, 128 and 158 cm above ground, see Figure 1 and details in section 2.2). Temperature measurements were performed using Pt100 sensors at 10 heights, i.e. 5 cm above and below each k_T probe. All snow measurements were controlled by a single data logger, interfaced with a multiplexer for temperature measurements, and two multiplexers for k_T measurements.

We address below the impact of snow compaction on the experimental design. First of all, the campaign was terminated before the melt season started. Snow height was therefore mostly driven by accumulation and compaction. Field inspection of the vertical structure of the snowpack revealed that distinct snow layers were relatively thick (10 to 20 cm generally), so that there is little chance that a given k_T probe was exposed to various snow layers throughout the field season, although the needles were progressively bent at their base. This has no impact on the k_T measurements because all the needles remained straight, but translated the experiment initially designed as Eulerian into a pseudo-Lagrangian one. The maximum height change of the middle of the heated section of each needle did not exceed 4 cm. Efforts to eliminate this issue will be made for the upcoming snow seasons.

2.2 Analytical technique employed for k_T measurements

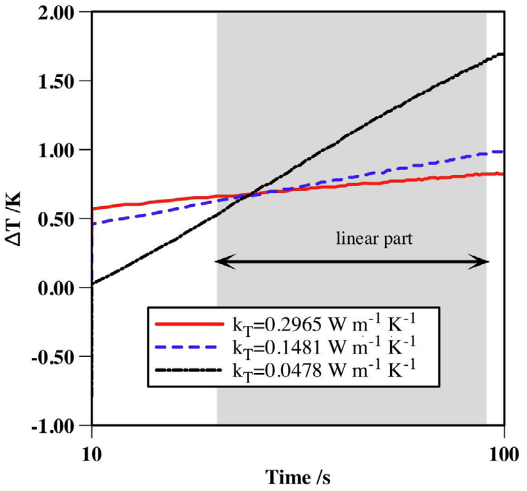

Figure 2: Typical thermograms (ΔT vs. time in logarithmic scale) for three different k_T. The value of k_T is obtained from the slope of the curves in the shaded area.

We briefly introduce below the heated-needle probe technique used to measure k_T. A needle (∅1.5mm, 15 cm) is heated over a length of 10 cm (see Figure 1) at a constant power during a short period of time (100 s). During this period of time one records the temperature difference (ΔT) between the middle of the heated section of the needle and a reference sensor situated at the extremity of the needle (see Figure 1b). This allows to quantify the rate of dissipation of the heat produced by the needle, which is inversely proportional to k_T (see e.g. Sturm et al., 1997 for details). Of particular significance for measurements in alpine snowpacks is the fact that this technique cannot be used at temperatures close to 0°C, because the moderate temperature increase that occurs during the measurements (on the order of 1 to 2 °C maximum) would induce melting of the snow, thereby irreversibly destroying the snow microstructure From the temporal record of ΔT one draws the thermogram shown in Figure 2. The slope of the ΔT vs. time on a logarithmic scale trace in the thermogram is inversely proportional to k_T, once a linear regime is attained (i.e. between 20 and 90s into the 100s time period during which the needle is heated).

One major advantage of carrying out k_T measurements using probes embedded in the snow is that perfect thermalization conditions are met. This reduces greatly the uncertainty of the measurements. Indeed, conventional field measurements are generally made only after a very short thermalization time (a few minutes), which does not prevent changes in the reference temperature and affects the precision of the measurements. Overall, the precision of the measurements carried out during the field campaign is estimated to be on the order of 2% and always better than 5%, based on the goodness of fit of the thermogram and the sensitivity of the k_T value to the time window used for the fit (Figure 2). Typical measurements in a snow pit are generally reproducible within 10%, owing to bad thermalization, but also horizontal (within a given layer) variability in k_T.

2.3 Implementation and quality insurance of the k_T measurements

k_T measurements were automatically performed once every two days at 5:00 UTC. Measurements were performed in the early morning to secure the coldest possible conditions in the uppermost snowpack. No measurement was undertaken if the maximum snow temperature was above -2.5°C. Figure 3 shows that k_T measurements were interrupted two times during the field campaign due to this reason (following the second interruption, the threshold was raised to -1.5°C).

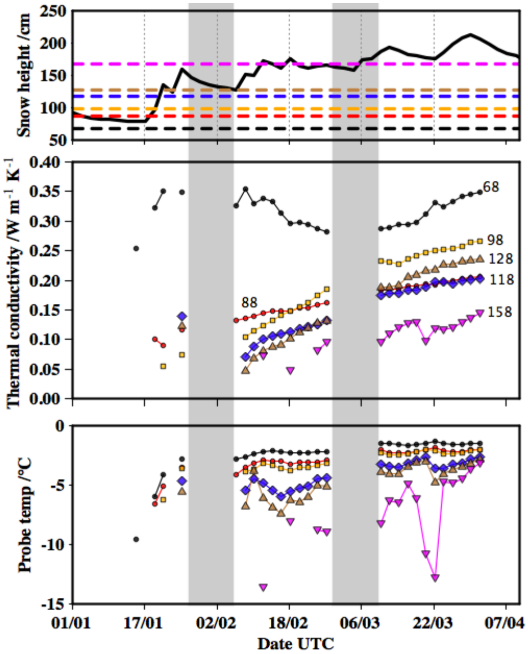

Figure 3: Overview of the physical variables of the snowpack, as measured once every two days at 5:00 UTC. k_T and snow temperature data are given for the 6 heights of the k_T probes. Shaded areas correspond to the periods of time when k_T measurements were interrupted due to too high snow temperatures.

Because of the active nature of the k_T analytical technique, sample disturbance induced by the warming up of the snow sample probed must be considered. However the short heating time (100s), the moderate temperature rise (maximum 1.7 K) and the low frequency of the measurements (once every two days) make this effect negligible. In addition the vertical profile of the automated k_T measurements compares very well with measurements carried out in a snow-pit dug a few meters from the measurement site on February 18, 2009, that is more than a month after the start of the field operations (see Figure 4). This additionally shows that the automated k_T measurements are representative of the thermal properties of the snowpack at the scale of several meters horizontally.

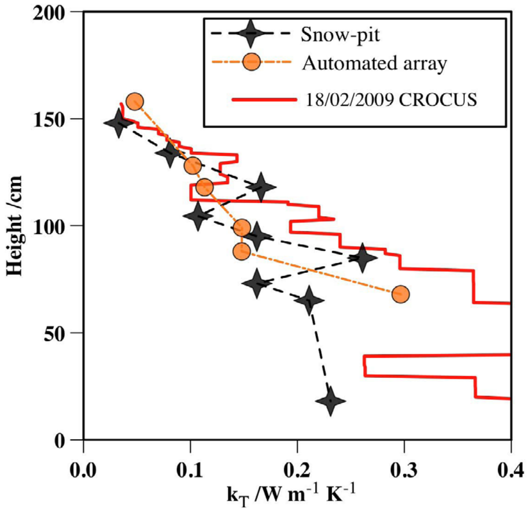

Figure 4: Comparison between the kT profile measured in a snow-pit and by the automated array on the same day.

3 RESULTS AND DISCUSSION

3.1 Temporal rate of change of k_T at various heights in the alpine snowpack

Figures 3 and 5 show an overview of the k_T measurements collected during the campaign, along with ancillary data. k_T ranges between 0.04 W m^{-1} K^{-1} (freshly fallen snow) and 0.35 W m^{-1} K^{-1} (dense snow at the bottom of the snowpack). In what follows we focus on the 4 probes at intermediate heights in the snowpack (88, 98, 118 and 128 cm). Indeed, the lowermost probe shows a peculiar pattern with a marked decrease in k_T during half of the measurement campaign (see section 3.3). The uppermost probe shows more variations in k_T which is simply due to the fact that this probe was embedded into a succession of different snow layers.

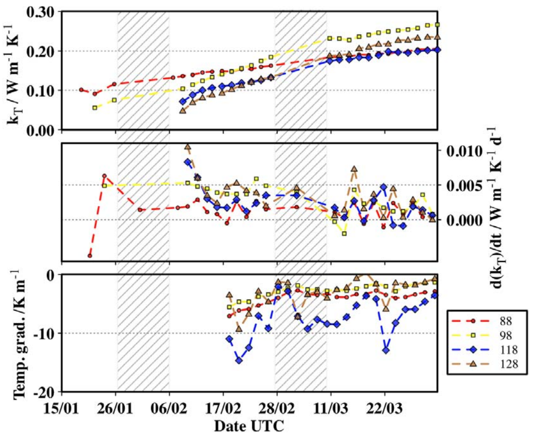

Figure 5: k_T, its rate of change, and the corresponding temperature gradient for four selected k_T probes (88, 98, 118 and 128 cm height)

As is commonly observed (Arons and Colbeck, 1995), k_T increased over time. Whenever the probe was in contact with freshly fallen snow, the measured k_T was on the order of 0.04 to 0.06 W m^{-1} K^{-1}. k_T then progressively increased. The temporal rate of change of k_T was maximum shortly after snowfall for a given snow layer (rates typically above 0.005 W m^{-1} K^{-1} d^{-1}), then decreased over time within the 0.000 – 0.005 W m^{-1} K^{-1} d^{-1} range. Such variations led to k_T values on the order of 0.15 to 0.25 W m^{-1} K^{-1} only a few weeks after snowfall, highlighting that thermal properties of snow layers evolve quickly over time.

Figure 5 shows the above-mentioned k_T temporal rates of change along with vertical temperature gradients relevant to each k_T probe. This shows that, except on a few occasions, vertical temperature gradients remained lower that 10 K m^{-1} i.e. in the "low temperature gradient" regime (Sommerfeld and LaChappelle, 1970). Under such conditions, the value of the temperature gradient itself probably did not drive changes of k_T.

3.2 Comparison with the predictions of the CROCUS snowpack model

Field measurements of k_T were compared with the output of the snowpack model CROCUS (Brun et al., 1989, 1992). Meteorological input to the model was provided by the meteorological station at the experiment site. Precipitation was obtained through the daily survey carried out at a ski resort nearby (Lognan).

As indicated above, it is worth mentioning that k_T is described only as a function of snow density in the CROCUS model, according to the empirical formulation of Yen (1981):

$$k_T = 2.22 \times (\rho_s/\rho_w)^{1.885}$$

where ρ_s (ρ_w) is the snow (water) density. Snow density was quite accurately simulated by CROCUS, as demonstrated in Figure 6.

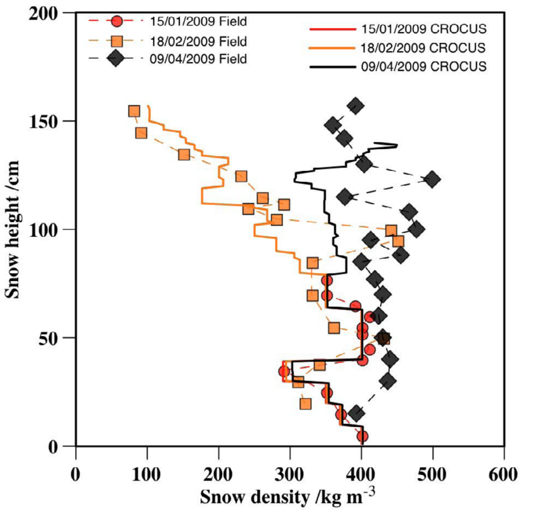

Figure 6: Comparison of the density profile measured in the field on 3 days, and simulated by CROCUS.

Figure 7 shows the profile of k_T calculated from the density predicted by CROCUS during the field campaign, along with the k_T measurements. Overall a good agreement between measurements and model predictions of the vertical profile of k_T was attained, which is mainly due to the monotonous trend of k_T vs. time. However, such field measurements could be more interestingly compared to sophisticated approaches to determine k_T as a function of snow-type and snow physical variables (inter-grain bond size etc.; e.g. Lehning et al., 2002).

3.3 A case where k_T decreased over time ?

Our experiment yielded an interesting observation from the probe situated at the lowest height in the snowpack (68 cm, see Figure 3). This probe was the only one physically inserted in a dense wind slab at the beginning of the experiments (other probes were buried by subsequent snowfall). k_T first showed an increase from the initial value of 0.25 to 0.35 W m^{-1} K^{-1} (over a time scale of a few days). Then, k_T started to decrease, and reached a value of 0.28 W m^{-1} K^{-1} after 20 days. This apparent decrease was linked to (and is consistent with) the observation that facetted crystals appeared in the snowpack at this height, despite low temperature gradients conditions (Arons and Colbeck, 1995, and references therein). After the decrease, k_T increased again and reached a value of 0.35 W m^{-1} K^{-1} towards the end of the field season. Clearly this observation cannot be reproduced by a model like CROCUS, because modeled density can only increase over time in dry snow. Nevertheless, this observation deserves further investigation and attempts to reproduce it at the very bottom of the snowpack will be undertaken during the next snow season.

4 CONCLUSIONS

Our study has demonstrated the feasibility of performing long-term (seasonal-scale) measurements of the vertical profile of k_T of the snowpack. The method employed induces negligible micro-structural perturbations. The implementation of a vertical array of "heated-needle" k_T probes during a 3-months-long field season has documented, for the first time, the rate of increase of k_T within several snow layers. The general observations that k_T increases over time is moderately well reproduced by the snowpack model CROCUS, although specific situations (e.g. decrease in k_T at the bottom of the snowpack) cannot currently be predicted by such a model.

We suggest that further experiments (both in the field and in the lab) under conditions exhibiting larger temperature gradients will probably shed more light on the intricate links between temperature gradients in the snow and the magnitude of snow metamorphism as revealed by the temporal rate of change of k_T.

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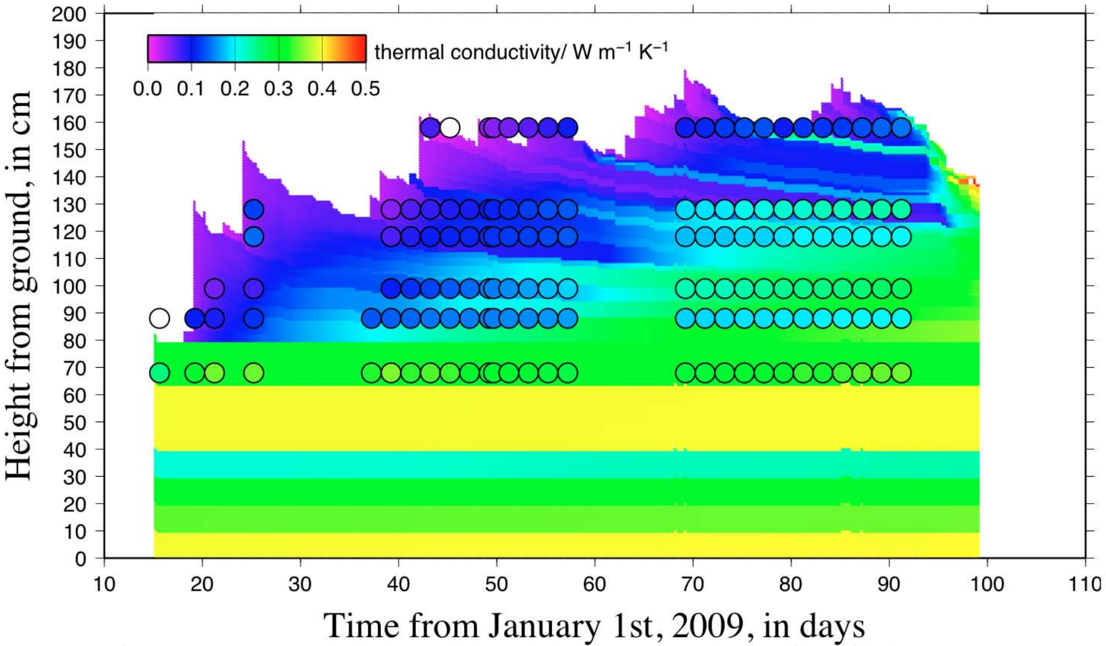

Figure 7: Comparison in terms of k_T between the snowpack model CROCUS and the field measurements.