

Responses to Reviewers' comments

The Reviewer's comments are in black, and our response is embedded in the text, in blue italics. Line numbers refer to those of the version in track changes mode.

5 Reply to Reviewer 1

General comments: The paper analyzes measurements of thermal conductivity of snow and soil in the Arctic, specifically at Bylot Island, Canada. Measurements occurred through 3 field seasons, and values compared to other studies, and to modeled values from the French snow model Crocus. Results are very interesting since it is suggested that a bi-modal distribution can be used to characterize the soil thermal conductivity. Simulated values from Crocus are contrary to measurements, the authors explain this by the absence of upward vapor flux from temperature gradient in the model.

Overall, the analysis and measurements are thorough and are quite relevant for the improvement of snow modeling in the Arctic, which remains poor. This paper provides insights on improvements needed for a better assessment of climate variability in the Arctic. I recommend this paper for publication in The Cryosphere, after minor revisions detailed below.

15 *Thank you for these positive comments.*

Specific comments:

Section 2.1: The authors describe the vertical locations of NPs and thermistors. One was moved following observations of depth hoar height. Furthermore, the chosen height for the other NPs and thermistors seem to be motivated by stratigraphy, which makes sense. However, such detail is not mention. It would be nice if the authors explain the reasoning behind the 2-12-22cm heights for NPs, and the 2-7-17-37 for thermistors? Also, why are thermistors at different height than NPs? They seem aligned with the initial positions of the NPs (7-17-27), why were they not lowered to match the NPs?

NPs were initially placed arbitrarily before we had a chance to observe the snow. Subsequently, thermistors were not moved to allow heat flux calculations. This is now mentioned lines 84 and 87.

25 I will leave to the discretion of the author to include a map of Bylot to Figure-1.

We have now added a map.

Line 142: I would clarify why depth hoar are more conductive in the vertical direction (i.e. owing to the higher thermal conductivity of ice relative to air, and an elongated grain). . . And why is it more conductive horizontally in wind slab?

30 *This is detailed at length in the references given (Calonne et al., 2011; Riche and Schneebeli, 2013), and we feel that repeating this here would unnecessarily lengthen the paper.*

Section 2.3: Although the modeling is described in details elsewhere, I would put a little more details here, otherwise the section can be removed and stated elsewhere since it is only 2-3 sentences long. The authors could simply add the data that was missing, the reasoning using ERA, and how Crocus computed thermal conductivity. The conclusions are significant with regards to Crocus, and more context need to be provided here for the reader's understanding.

35 *We have added a brief sentence regarding ERA and mention how thermal conductivity is calculated in Crocus, using a simple correlation with density (lines 179-181).*

Figure-2 has very poor resolution and consequently very hard to read.

We have improved Figure 2.

40 Section 3.1: I assume SSA are from DUFISSS? This should be mentioned in the paper .

Yes, this was already mentioned in the methods section (now line 165)

Figure-6: dates are in French

Not just Figure 6. This has been corrected throughout.

45 Section 4.3.: A figure on Crocus output, visualized profile with marks on the melt event would greatly help the understanding of this section. The authors could display Crocus thermal conductivity and snow temperature (or temperature gradient). The problem of density profiles and simulated grains would be more obvious.

50 *Do we really need an extra Figure while other Reviewers request condensation? One of the main points is really that Crocus predicts melting in the early season and does not predict the transformation of the melt-freeze crust into depth hoar, and this is well detailed. Note that if the editors request so, we will add a Figure showing the evolution of snow stratigraphy over the season, as predicted by Crocus, and the reader can compare that to Figure 2. The danger is that since spatial variations are important, over-interpretations of the differences may be made.*

Reply to Matthew Sturm

55 In this paper the authors report on the evolution of the thermal conductivity (k_{eff}) of the tundra snow cover of Bylot Island. It is an interesting paper, with a key finding being that the contrast in k_{eff} between depth hoar and wind slab is on the order of 1:10. While this finding is not new, it is a useful piece of information that is neither widely appreciated nor captured by snow models (as the authors show). Overall, I recommend the paper be published....but not until it has been shortened considerably. The number of readers who will want to wade
60 through all the detail currently in the paper in order to glean the main points is limited, and as consequence, the impact of the paper will be reduced

*Thank you for this overall positive comment. Time will tell what the impact of the paper will be. The paper does not just present snow data but also original soil data, which are currently very scarce in the literature. Furthermore existing monitoring data on soil thermal conductivity arguably suffer from artefacts. Here, by minimizing the heating power of our needle probes, we argued that we
65 limited some artefacts, and we feel that this adds interest to our data. Regarding the length of our paper, we feel that establishing links between meteorological events and the evolution of the thermal conductivity of snow deserves detailed discussions. For example, a detailed understanding between wind speed and wind slab physical properties such as thermal conductivity is critically needed. Current parameterization of wind effects is based on limited knowledge (see
70 e.g. (Vionnet et al., 2012)) and at least some modellers will doubtless appreciate these details: some want to move away from simple and inaccurate density-thermal conductivity correlations. Lastly, the reviewer, while recommending considerable condensation, also requests numerous very lengthy additions. Doing both does not seem easy...*

75 One other key point: if the 1:10 contrast in k_{eff} is the big take-away message of the paper, then the authors have missed an opportunity to discuss a key aspect of how tundra snow functions, in a way that is convolved with this 1:10 contrast. As seen in the authors' Figures 2 and 7, the relative percentage of depth hoar vs. wind slab controls the bulk thermal conductivity of tundra snow covers to a large extent. The number of windstorms, the relief of the underlying tundra tussocks (inter-tussock depth hoar), and the sequence of snowfall events all
80 combine to determine what these percentages will be, hence how conductive the snow cover will be. This is a sensitive balance, one that could easily change if the climate, wind regimes, and snow-up dates, change. Discussing this would be valuable and for those readers that this paper aims at possible new information.

*Such a discussion would deserve a paper on its own, and in any case this is not compatible with the considerable text condensation recommended above. We nevertheless address this issue in
85 section 4.1 of the discussion, and mention how threshold effects will lead to the abrupt transition between depth hoar and wind slab (lines 375-379). Thresholds may be reached by a sudden snow accumulation episode, whether caused by precipitation or wind. Note that the Reviewer stresses the tussock-type topography, which is frequently encountered on the Alaska North slope where he has done extensive work. This does not exist here, although hummock microrelief exists but not at
90 our very site, and we therefore cannot discuss that here.*

Other specific comments follow:

1. The authors have a tendency to cite new rather than seminal work, and philosophically, I find this distressing. It leads to the field "forgetting" facts and findings, then these have to be rediscovered. For example, that there are
95 large amounts of organic matter in the permafrost was well known and reported on in the 1960s and 1970s: see Lachenbruch and Ferrians among other authors. A similar comment on references in the snow literature.

*We agree with the Reviewer that we do not mention many seminal references. However, for the sake of concision, this was intentional and there are several reasons for this. For example, in the case of organic matter in the permafrost, we feel that this aspect, although important for many
100 purposes, is not critical for our work, and we therefore do not wish to review it, even shortly. We*

therefore feel that a single recent (and therefore more complete) reference (Hugelius et al., 2014) is sufficient to inform the reader on the subject. Readers interested in more detail can look through the very many references of that paper. Regarding seminal snow references, we agree that there are many seminal references relevant to this work such as the work of Akitaya and in particular (Akitaya, 1975). However, again, our purpose is not to review depth hoar studies. In fact, Akitaya's work is not very relevant to Arctic depth hoar, as the Reviewer subsequently mentions, and we prefer to cite more relevant work, which by the way we find just as seminal, e.g. (Sturm and Benson, 2004; Sturm and Benson, 1997). And again, we are urged to remain concise and try to do so. Regarding soil thermal conductivity, we do cite seminal work, such as (Penner, 1970), line 138.

2. Line 117: Convection in snow. This was a lot of attention paid this topic in the 1980s and 1990s. The authors should see and cite:

Powers D, O'Neill K, Colbeck SC (1985) Theory of natural convection in snow. Journal of Geophysical Research 90:10641-10649.

Sturm M, Johnson JB (1991) Natural convection in the subarctic snow cover. Journal of Geophysical Research 96 (B7):11657-11671.

Sturm M (1991) The Role of Thermal Convection in Heat and Mass Transport in the Subarctic Snow Cover. USA-CRREL Report 91-19.

Indeed, we are well aware of these references. However, those papers deal with natural convection in the snow cover. Here, we only briefly discuss convection induced by the heating of the needle, which in this case causes an artefact. We therefore believe that natural convection is not directly relevant to this discussion and again, to remain concise, we feel that it is not essential to discuss it here.

In response to a comment by Reviewer 3, we invoked natural convection to explain the irregular collapse of depth hoar and cite (Sturm and Johnson, 1991), line 387.

3. Line 151: Alternate methods of measuring thermal conductivity: It is not clear that guarded hotplate methods would produce more accurate or appropriate values k_{eff} . ---just different. While the dynamic method of the needle probe has some problems (pointed out by the authors) so too do steady-state methods. For example, real snow covers rarely, if ever, develop a steady-state non-varying temperature gradient. Also, when snow is subjected to uni-directional gradients, the thermal conductivity evolves through metamorphism, leading to a varying value of k_{eff} (or alternately, such mild gradients have to be imposed that the resultant tests are equivocal). I suggest altering the statement to indicate that the alternate methods are impractical, and *may not even be more accurate.*

This is currently a very controversial topic. Our understanding of this issue differs from that of the Reviewer. Clearly, it would be in our interest to be able to state that needle probes have no disadvantage relative to other methods. However, we feel that the recent work of (Calonne et al., 2011) and of (Riche and Schneebeli, 2013), which we cite in our paper, fairly convincingly point to a systematic error in needle probe measurements. We discuss this in detail in our earlier work (Domine et al., 2015). We briefly reminded the main important points of our earlier discussion lines 142 to 161. The Reviewer points to possible problems with steady state methods, and he is certainly correct: no current method to measure snow thermal conductivity is fully satisfactory, but we feel that current evidence does point to more problems with the needle probe method, which we must mention for full information of the reader. Fig. 6 of (Riche and Schneebeli, 2013) nicely sums up some aspects of the problem. By the way, we are not sure to understand the argument that natural snow covers do not develop a steady state temperature gradient. Perhaps the Reviewer is suggesting that steady state method may be used for thermal conductivity monitoring, but we probably all agree that this is not possible.

4. Line 156: Do you have to worry about pore water migration in measuring thermal conductivity of the soil using a needle probe?

This would be the equivalent of convection when measuring thermal conductivity in snow. We have never seen this aspect mentioned and do not expect it to be important given the very low permeability of soils. In any case, it is certainly much less important that problems due to melting, which we discuss in detail in section 4.4.

5. Lines 185 and 265-270: **Indurated depth hoar**. I would like to see a more comprehensive discussion of this snow texture. I believe the lead author and I discussed this snow texture when working jointly on snowpits in Alaska about a decade ago. He is correct that no formal symbol for the material exists in the International Classification, but that arises in part from the fact that I don't think the committee charged with revising the classification believed such a material existed. The symbol I have been using for almost 20 years for this type of snow is a combined symbol of wind slab (black circle with a slash) and depth hoar (chains of grains or just cups). This is not that different than the one introduced in the paper, and it would be good to mention both as many of my students continue to use our older symbol. In addition, Carl Benson and I described this texture in our 1993 paper the phenomenon, though it was a few years later I introduced the term "indurated":

Elsewhere wind slabs are adjacent, one on top of the other. As the winter progresses even dense wind slabs can begin to metamorphose into depth hoar. We have observed wind slabs as dense as 0.35 g cm metamorphose into depth hoar by the end of the season.

Before introducing that term I corresponded with Dr. Akitaya (arguably at the time *the* expert on depth hoar) regarding it. He had never seen this texture in Japan because the temperature gradients are too low to produce it.

Indeed, FD does remember well this March 2004 discussion with the Reviewer near Barrow, Alaska. Indurated depth hoar is frequent in the Arctic and its absence in the international classification is a very big problem. FD mentioned this to Charles Fierz when he circulated drafts of the classification, but that steered no interest in the committee. We therefore fully agree that many world snow experts are familiar with mid-latitude snow, but have seldom seen Arctic snow, even though it is more prevalent. There is therefore a need to fully describe indurated depth hoar. We have done that lines 189-201, quoting the most detailed description we found, from (Derksen et al., 2009) and (Domine et al., 2016). We also discuss that indurated depth hoar can form not only in wind slabs but also in refrozen layers, and propose 2 symbols to differentiate both types. Additional details are given lines 302-308. We also mention the works of (Hall et al., 1991) and of (Sturm et al., 2002), who mentioned a snow type that was presumably depth hoar, although not named specifically. We also mention (lines 303-309) the symbols used by those authors but we feel the symbols we propose are more logical and above all allow differentiating whether indurated depth hoar formed in wind slabs or melt-freeze layers

6. **Temperature Gradients:** (Lines 313-317) In order to turn wind slabs into indurated depth hoar, strong gradients are needed (see authors Figure 11). While the gradients a Bylot Island are super-critical ($> 25^{\circ}\text{C/m}$) for much of the winter, they are less strong than I would have expected. I attach comparable data from Alaska's North Slope. Not only are the gradients stronger than those in the paper, but they start earlier in the winter. In a second graph, I have smoothed the data (48 hour running average), as the authors have done. The result is noticeably milder. I suggest the following changes/additions: a) don't smooth the gradients. In 48 hours a lot of metamorphism can take place. Smoothing makes the graph cleaner but less "physical" as far as metamorphism is concerned, b) show the critical gradient....whether that of Marbouty or Colbeck or Armstrong. It gives readers an appreciation of what drives the changes, c) consider computing something like an integrated metric called "time under a strong gradient" or the like. Right now the paper mainly focuses on the agreement between the thermistor and NP values, but that misses the BIG point of what is actually driving the physics. And while Lines 325-330 provide the vapor gradient (and state that it can grow depth hoar), the values are really meaningless unless they are translated into something like a growth rate. Consider as an example computing how fast these vapor gradients could grow a thin sheet of ice...like the skirt on depth hoar cup. That would make the values mean something.

We have replaced the smoothed by the unsmoothed gradient in Figure 11. Values are a little bit greater, but not much: the highest value is 104 K m^{-1} vs. 87 for smoothed values. Gradient values are then just lower than in Alaska 25 years earlier. Higher values were probably reached earlier in the season but we need more than 12 cm of snow to measure it, since this is the level of our second NP. Our thermistor at 7 cm height would have given us the early season data, but as mentioned in the paper, the cable was chewed by a fox. This is detailed lines 355-361.

Following also the recommendation of Reviewer 3, we have calculated the water vapor flux, which is in fact what drives metamorphism, rather than the temperature gradient. We discuss threshold values and their relation to snow accumulation (lines 376-380). However, we do not wish to insist on “critical gradients” as we believe these have little physical meaning for Arctic snow. The real important physical variable is the water vapor flux, and we focus on that (Figure 12 and lines 366 ff.). The “critical gradient” was meaningful for Alpine and temperate snow, when the warmer temperature of the gradient was always close to 0°C . In Arctic snow, the warmer temperature can be as low as -35°C (Figure 3) so that the flux here, for a similar gradient, will be 15 times lower than if the warmer temperature were 0°C . We therefore think that reasoning on gradients for Arctic snow is misleading and we do not wish to follow that avenue.

8. Soil to Snow Fluxes: These have been measured during depth hoar metamorphism. See:

Trabant D, Benson CS (1972) Field experiments on the development of depth hoar. *Geological Society of America Memoir* 135::309-322.

Santeford HS Snow Soil Interactions in Interior Alaska. in Modeling of Snow Cover Runoff, USACRREL, Hanover, NH, pp. 311-318.

Sturm M, Benson CS (1997) Vapor transport, grain growth and depth hoar development in the subarctic snow. *Journal of Glaciology* 43:42-59.

We mention (Sturm and Benson, 1997) line 409 and compare our soil water loss value to theirs line 413. The other 2 references could not be found.

9. Line 341: There is a large literature on depth hoar and subnivean animals. Possibly the best starting point is W. O. Pruitt's 1957 paper: □ Pruitt Jr, W. O. (1957). Observations on the bioclimate of some taiga mammals. *Arctic*, 10(3), 130-138.

Indeed there is, but further developing this aspect is not compatible with condensing the manuscript and with Reviewer 3's recommendation to even remove this section. We therefore limit ourselves to citing the work done at our research site, adding the recent results of (Fauteux et al., in press) which allow us to relate in a very preliminary manner our observed snow properties with lemming populations (lines 433-438).

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Penner, E.: Thermal conductivity of frozen soils, Can. J. Earth Sci., 7, 982-987, 1970.

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Reply to Martin Schneebeli

General comments

The is an interesting study, which shows in detail the enormous problems to measure, monitor and interpret thermal conductivity of snow under field conditions in the high arctic. The paper shows that large uncertainties exist in measurement and in the application of models, and that a continuous monitoring is difficult. In fact, the results suggest that simple density measurements and the now very well calibrated parameterizations, maybe a more feasible and precise way to observe the evolution of the snowpack. The interpretation of the measured thermal conductivities of the needle probe are in my view not always supported by other the other data presented in the paper, as will be discussed below in detail.

Thank you for this overall positive comment. We however do not agree with the suggestion that density measurement and the use of density-thermal conductivity correlations would be a good method to estimate thermal conductivity. We discuss this below with the relevant comment.

The discussion on subnivean life is a bit out of focus in this paper, clearly an important aspect of the arctic snow cover, but in my view not the right place.

This is a matter of view point. The reviewer is an Alpine snow scientist and some of his main interests include avalanches and snow microstructure. We focus on Arctic problems and subnivean life is critical. In fact, although the main motivation of this program is permafrost thermal regime, another important objective is subnivean life. Please remember that lemmings form the very base of the terrestrial food web (Gauthier et al., 2011) and understanding their life conditions is critical for any Arctic wildlife dynamics consideration. Most Arctic snow scientists always have subnivean life in the back of their mind, but on the other hand very few ever think about avalanches. We do intend to use snow thermal conductivity as a proxy for lemming-relevant snow properties, as explained in our paper (lines 63-64) and we therefore feel this discussion fully belongs to this paper. In fact, a very recent study by (Fauteux et al., in press) shows population variations between 2014 and 2015 that appear consistent with our snow observations and we have added a short paragraph in the discussion to mention this (lines 433-438).

Specific questions:

The authors interpret thermal conductivities in snow around $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ as snow conductivities (they mention that this is within errors the same value as in air). I believe there are two points not made clear: The snowpack, if the bottom layer would be air over an extended area, would immediately compact (in fact, avalanche formation mechanics gives an upper bound of about max. 1 m^2 air gap before an spontaneous collapse of the snowpack forms). The "close-to-air" values are therefore at least not spatially representative.

The reviewer probably misunderstood our statements. We say clearly in the results section that these values are for depth hoar and that they are a bit low and close to that of air because of the negative artefact due to the use of the NP method. Our lines 227-229 read: " k_{snow} dropped to values around $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ because of rapid depth hoar formation. These values may seem a bit low, especially considering that air has a thermal conductivity of $0.023 \text{ W m}^{-1} \text{ K}^{-1}$, but the low value can be attributed to a negative systematic error of about 20% caused by the NP method, as described in (Riche and Schneebeli, 2013) and discussed above."

Regarding the presence of air at the bottom of the snowpack, the reviewer probably misunderstood our statements. We never say that air is continuously present over extended areas. Rather we clearly show the discontinuous nature of these air gaps in Figure 8. Furthermore, spontaneous collapse of the snowpack is predicted for Alpine conditions where snow is thick and the overburden significant. In the Arctic, very different conditions prevail with a thin snowpack (as clearly stressed in Figures 2, 3, 6 and 7) and hence a much lighter overburden. Finally, the values measured are for snow and definitely not for air. Measurements in air are almost always very easy to recognize: heating curves are erratic because of the complex and irregular convection that always takes place. This was alluded to in the methods section (lines 127-130) and we now further

stress the point line 230 *"It is fairly certain that this NP was not in an air gap, because measurements in air almost always produce erratic heating curves due to complex convection, and none of the heating curves were suspicious."* We therefore believe that, even though there are clearly spatial variations, our values are representative and this is supported by the field data of Figures 2 and 7, with values similar to the automatic measurements.

The inclusion of the soil in the interpretation is very useful, except that no detailed granulometric soil analysis seems to exist as this is a well investigated research site? More detailed data would clarify the observed behavior of the soil-freezing behavior. In fact, the observed curve indicates that the soil is not a silt, but a fine sand.

This is an excellent point. Granulometric data was indeed lacking. We performed such an analysis using a Horiba partica LA-950V2 laser scattering particle size analyser. Data show a bimodal size distribution with modes centered at 17 and 59 μm . If the standard 50 μm size limit between sand and silt is used, then our sample is 65% silt and 35% sand by mass. A subsection was added to our methods section to describe briefly the method (lines 171-174). The results are now mentioned lines 258-261.

The authors put substantial weight on the effect of water vapor fluxes on the snowcover. The explanation of the fragile depth hoar bottom layer, as well as the formation of indurated layers, is based on the interpretation of temperature and vapor pressure gradients. The calculation of the vapor flux is omitted with the argument that the diffusivity is not well known. Laboratory experiments and numerical simulations (Calonne, 2014; Pinzer, 2012) defined the diffusion coefficient precisely - in fact, due to the hand-to-hand process, the diffusivity in air is a very precise approximation. Approximate calculation for the season 2014-2015, with an average snow temperature of -30 deg C, temperature gradient 50 K m⁻¹, and a duration of 90 days, result in a mass flux of 0.24 kg m⁻². This flux seems to me too small to explain the observed processes.

Thank you for this very useful comment and for taking the time to make the calculation. Using the data of Calonne et al., we have calculated water vapor fluxes and these are now shown in Figure 12. Our calculations lead to a total mass loss about 10 times greater than the Reviewer's estimate, because he used a temperature of -30°C while in the lower part of the snowpack, especially in early season, the temperature was around -5°C, so that the water vapor pressure was about 10 times greater. In any case, we agree that this is not quite sufficient to fully explain the total snow collapse. We therefore now suggest that diffusive fluxes alone cannot explain our observations, but convection and air advection (wind pumping) probably also took place and must have contributed to the mass loss, explaining the observation. The presence of convection cells is fully consistent with our observation of irregular collapse (Figure 8). This is now detailed in the discussion, lines 381-395.

Obviously, spatial variability of the thermal conductivity of snow cannot be measured by permanent stations. However, as is obvious from the snow profile and the descriptions, spatial variability is an issue at the dm - m scale. As a suggestion, long snow profiles as done by Rutter et al (2014) in the arctic, or as demonstrated using a penetrometer by Proksch et al., would have contributed much to reduce the uncertainty in the measured values and their interpretation.

Indeed, more measurement would have been highly desirable, as always, but there is only so much we can do in a 10-day campaign with complex logistics, multiple objectives and occasionally uncooperative weather. We did however investigate the spatial variability of the density of the depth hoar layer as shown in Figure 2. Figure 8 a and b also illustrate this variability.

The use of needle probes as monitoring devices is strongly defended by the authors. However, a careful inspection of their Fig. 2 and Fig. 13 a) and calculating thermal conductivity based on the well accepted Calonne et al (2011) parameterization (or the Yen-parameterization) using the measured density, shows that the needle probes underestimate severely (for depth hoar a factor of about five) the effective thermal conductivity.

Thank you for this interesting comment; however we have to disagree with the reviewer. First of all, we do not "strongly" defend the use of the heated needle probe. We are fully aware of its

limitations and artefacts (thanks in part to the reviewer's publications, by the way). We only state that today it is the only technology suitable for the continuous monitoring of snow thermal conductivity, but we'll gladly consider any alternative, when available. Second, we do not think that the parameterizations of either Calonne et al. or Yen et al. are well accepted. The parameterization of Calonne is based on 30 values and that of Yen on less than 60. Calonne et al. only measured Alpine snows and did not measure a single sample of low-density depth hoar. Most or all of the snows used by Yen are not Arctic snow. Given the huge difference between Arctic and Alpine or temperate snow, of which most snow scientists are not fully aware, we feel that it is not reasonable to attempt to determine the thermal conductivity of Arctic snow from very small and not representative data sets. Calonne et al., on their Figure 1, also report the 500+ values measured by (Sturm et al., 1997), all of them on Arctic and subarctic snow. These clearly show the huge difference between (sub)Arctic snow and Alpine snow, and demonstrates beyond doubt that parameterizations not developed for Arctic snow simply should not be used for Arctic snow. The large data set of (Sturm et al., 1997) also shows that for a given density, the range of thermal conductivities varies by a factor of 5, so that density correlations cannot predict accurately Arctic snow thermal conductivity. We admit that needle probes may underestimate the thermal conductivity of depth hoar, and we did mention that in our paper, but this effect is simply not sufficient to warrant the use of the parametrization of Calonne et al. or Yen to understand Arctic snow thermal conductivity. We have added a paragraph to our discussion (lines 467-476) to detail all this.

The numerical simulation using Crocus seems to have major problems with creating a realistic density profile. As no details are given, my conclusion is that severe deficiencies must exist in the model parameterization. I suggest that the model runs are checked by an expert, as they seem to me beyond any reasonable behavior, or this part of the manuscript should be deleted.

Full details of the model are given in (Domine et al., 2016), so we do not feel it is useful to repeat them here. The model runs were in fact performed for that earlier paper, of which Samuel Morin is a co-author, and he has an extensive record of publications using Crocus. The problem is not the model parameterizations or our use of the model, the problem is that the model has been developed for Alpine snow and does not take into account vertical water vapor fluxes. To fully convince the reviewer that this is the problem, we asked our colleagues Alexandre Langlois and Jean-Benoit Madore (University of Sherbrooke) to perform runs with SNOWPACK, the detailed snow physics model of the Reviewer's institution. They used NARR forcing data. Figure 1 below shows data similar to those of Figure 13 in our paper, which we also show here to facilitate comparison.

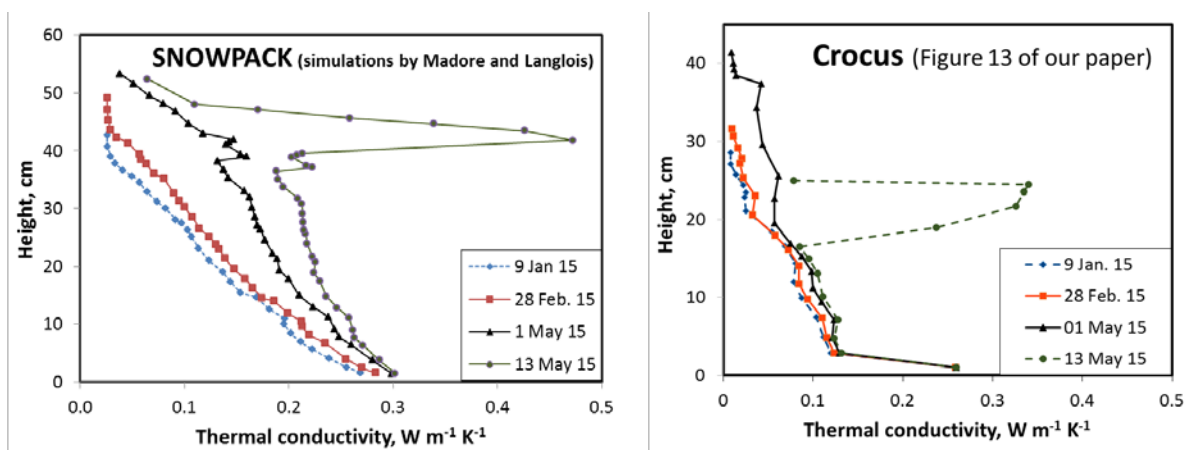


Figure 1. Simulations of snow thermal conductivity at Bylot Island using the SNOWPACK and Crocus models.

Neither Crocus nor Snowpack can reproduce the low thermal conductivity at the base of the Arctic snowpack and the high values at the top. We hope this will convince the Reviewer (and the Editor) that the problem is not our use of the model. The problem is that current detailed snow physics models (which include SNOWPACK and Crocus) miss what is arguably the most important process in Arctic snow: the upward water vapor transport due to the huge temperature gradient. Until this process is included in the models, sensible simulations of Arctic snow physics will not be possible. FD has been trying to get the message across for years, but most Alpine snow scientists (and that seems to be most snow scientists) do not seem to realize the importance of this process. We hope these results will help...

Technical corrections

1 200 These values are questionable based on the authors density measurements. If there is no heat conducting matrix, there is no mechanical (compressive) strength.

We believe we have discussed this in depth above. Again, density-thermal conductivity measurements cannot give accurate estimates.

1 230 Did the authors any calibration of the temperature and soil humidity sensors before or after the deployment?

In the methods section, line 91-92, we have added that "Water content sensors used the manufacturer's calibration for mineral soils and were not recalibrated, which may produce an error of up to 3%."

1 283 "Rise" -> rise

Corrected, thank you.

1 290 The same limitations concerning vapor flux are valid also for convection (if there is any with the measured snow profile). In my view the speculation is out of place.

As discussed above, water vapor fluxes are 10 times greater than estimated by the reviewer. Convection effects are also probably greater.

1 317 ff The fluxes are easy calculate, this section should be rewritten in view of the actual fluxes.

Indeed. The fluxes have now been calculated and Figure 12 changed accordingly. This led to what we feel is a significant improvement. Thank you for your comments of this aspect.

Almost all Figures: The time axis is lettered in French, not English

Changed.

Fig. 1 The appearance of the vegetation in the photo seems to involve some vertical structure, completely flattened out during early winter? Not unimportant for the interpretation of the depth hoar formation.

We now mention (lines 78-79) that "Vegetation consists of sedges, graminoids and mosses". In the results section, we also mention "Vegetation was observed to be mostly flattened by snow, with some sedge or graminoids stems still upright, but they did not seem to have impacted snow structure." lines 188-9.

Fig. 2 The symbol for melt-freeze indurated depth hoar is actually defined (Int. Class., p. 19, a lying "8" with depth hoar symbols inside)

We could not find this in the classification on p. 19 or elsewhere. The lying 8 on p.19 has circles inside. The word "indurated" is mentioned only once in the whole document, in the footnote of p. 17 and there is no associated symbol.

Fig. 3 Snow depth or snow height. Caption, text and axis are not consistent (also Fig. 6)

Thank you. For snow, we now use height throughout. We use depth for soil.

Caption Fig 3: where there no easy measurements of snow depths around the stations to know spatial variability around?

Sure, we apologize for failing to detail this. We have now added line 202 that “Measurements using an avalanche probe at 236 spots within 200 m of our site on 12 May 2015 showed a mean snow height of 25.3 cm, with a standard deviation of 13.1 cm”. We make a similar statement on line 264 for the 2014 season.

Fig. 7 The measured thermal conductivity data are inconsistent with the density profile. Give error bars.

We hope that the above discussion will convince the reviewer that they are perfectly consistent. This is Arctic snow, not Alpine snow. Errors on measurements are detailed in the text. For example, in line 227, we specify that “the low value can be attributed to a negative systematic error of about 20% caused by the NP method, as described in (Riche and Schneebeli, 2013) and discussed above”. Adding error bars would be confusing, as these are normally used for statistical, not systematic errors.

Acknowledgement

We thank Jean-Benoit Madore and Alexander Langlois, University of Sherbrooke, QC, Canada, for making the SNOWPACK simulations of Figure 1.

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Seasonal evolution of the effective thermal conductivity of the snow and the soil in high Arctic herb tundra at Bylot Island, Canada

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Abstract. The values of the snow and soil thermal conductivity, k_{snow} and k_{soil} , strongly impact the thermal regime of the ground in the Arctic, but very few data are available to test model predictions for these variables. We have monitored k_{snow} and k_{soil} using heated needle probes at Bylot Island in the Canadian High Arctic (73°N, 80°W) between July 2013 and July 2015. Few k_{snow} data were obtained during the 2013-2014 winter, because little snow was present. During the 2014-2015 winter k_{snow} monitoring at 2, 12 and 22 cm heights and field observations show that a depth hoar layer with k_{snow} around 0.02 W m⁻¹ K⁻¹ rapidly formed. At 12 and 22 cm, wind slabs with k_{snow} around 0.2 to 0.3 W m⁻¹ K⁻¹ formed. The monitoring of k_{soil} at 10 cm depth shows that in thawed soil, k_{soil} was around 0.7 W m⁻¹ K⁻¹ while in frozen soil it was around 1.9 W m⁻¹ K⁻¹. The transition between both values took place within a few days, so that the use of a bimodal distribution of k_{soil} for modelling appears adequate, in contrast to conclusions from previous studies. This may be explained by different soil properties or by artefacts caused by using high heating powers for thermal measurements in previous works. Simulations of k_{snow} using the snow physics model Crocus were performed. Contrary to observations, Crocus predicts high k_{snow} values at the base of the snowpack (0.12 to 0.27 W m⁻¹ K⁻¹) and low ones in its upper parts (0.02 to 0.12 W m⁻¹ K⁻¹). We diagnose that this is because Crocus does not describe the large upward water vapor fluxes caused by the temperature gradient in the snow and soil. These fluxes produce mass transfer between the soil and lower snow layers to the upper snow layers and the atmosphere. Finally, we discuss the importance of the structure and properties of the Arctic snowpack on subnivean life, as species such as lemmings live under the snow most of the year and must travel in the lower snow layer in search of food.

Keywords. Snow, Soil, Thermal conductivity, Arctic, Permafrost, Subnivean life

1 Introduction

35 Arctic permafrost contains large amounts of frozen organic matter (Hugelius et al., 2014). Its thawing could lead to the microbial mineralization of a fraction of this carbon, resulting in the release of yet undetermined but potentially very important amounts of greenhouse gases (GHG, CO₂ and CH₄) to the atmosphere (Elberling et al., 2013; Schneider von Deimling et al., 2012; Schuur et al., 2015), resulting in a strong positive climate feedback. Predicting GHG release from permafrost first requires the prediction of the evolution of the permafrost thermal regime, which depends to a significant extent on snow and soil thermal conductivity. Several recent land surface model developments or improvements have indeed tested that these variables had a critical impact on ground temperature (Chadburn et al., 2015; Ekici et al., 2015; Paquin and Sushama, 2015). Snow in particular is often mentioned as a key factor in the permafrost thermal regime (Burke et al., 2013; Gouttevin et al., 2012). Yet, most land surface models which use an elaborate snow scheme often simply parameterize snow thermal conductivity as a non-linear function of its density. Even though the average density of snow may be adequately predicted in land surface models (Brun et al., 2013), the density profile of Arctic or subarctic snow is currently not predicted well by most or all snow schemes (Domine et al., 2013) because the upward water vapor flux generated by the strong temperature gradients present in these cold snowpacks (Sturm and Benson, 1997) is not taken into account. These fluxes lead to a mass transfer from the lower to the upper snow layers, and these transfers can result in density changes of 100 kg m⁻³, perhaps even more (Domine et al., 2013; Sturm and Benson, 1997). Given the non-linearity between snow thermal conductivity and density used in most snow schemes, errors in the snow density vertical profile inevitably lead to errors in the snowpack thermal ~~properties~~^{resistance} and therefore in the permafrost thermal regime.

Obviously, soil thermal conductivity is also important in determining vertical heat fluxes. For a given soil composition, this variable depends mainly on ~~This~~ variable depends on temperature and content in liquid water and ice, so that its value may show considerable variations over time (Overduin et al., 2006; Penner et al., 1975). Modellers of the permafrost thermal regime have stressed that “monitoring of this parameter in the active layer all year-round would be useful if a more realistic numerical model is to be developed” (Buteau et al., 2004).

Another important interest of studying snow physical properties such as thermal conductivity and the heat budget of the ground lies in the understanding of the conditions for sub-nivean life. For example, lemmings live under the snow most of the year at Bylot Island (Bilodeau et al., 2013), and the temperature at the base of the snowpack conditions their energy expenses to maintain body temperature. Furthermore, energy expense for sub-nivean travel in search of food depends on snow hardness and snow conditions have been invoked to help explain lemming population cycles (Bilodeau et al., 2013; Kausrud et al., 2008), even though no comprehensive snow studies have yet been performed to fully establish links between lemming populations and snow properties. Snow thermal conductivity has been shown to be well correlated with snow mechanical properties (Domine et al., 2011), so that monitoring snow thermal conductivity may help quantify the effort required by lemmings to access food and hence understand their population dynamics.

Given the importance of snow thermal conductivity to simulate the ground thermal regime and to understand the conditions for sub-nivean life, we have initiated continuous automatic measurements of the snow thermal conductivity vertical profile at several Arctic sites using heated needle probes (NP). The first instrumented site was in low Arctic shrub tundra (Domine et al., 2015), near Umiujaq on the East shore of Hudson Bay. We present here an additional study with two years of snow thermal conductivity monitoring at Bylot Island, a high Arctic herb tundra site (73°N, 80°W). Since lemming populations have been monitored there for over two decades (Bilodeau et al., 2013; Fauteux et al., 2015), the snow work undertaken here may indeed also help understand snow-lemming relationships. Additionally, we also placed a heated NP in the soil at a depth of 10 cm to monitor soil thermal conductivity in the active layer over the seasonal freeze-thaw cycles.

2 Methods

2.1 Study site and instrumentation

Our study site is on Bylot Island, just North of Baffin Island in the Canadian high Arctic. The actual site was at the bottom of Qalikturnvik valley, in an area of ice-wedge polygons (N 73°09'01.4", W 80°00'16.6"), in a context of high Arctic thick permafrost. This spot is within 100 m of that described by (Fortier and Allard, 2005). Our instruments were placed in July 2013 in a fairly well drained low-center polygon with peaty silt soil (Figure 1). Vegetation consists of sedges, graminoids and mosses (Bilodeau et al., 2013). The active layer is about 30 cm deep at our site and permafrost at Bylot Island is thought to be several hundred meters deep (Fortier and Allard, 2005). The site is only accessible with complex logistics, so that field work only takes place in late spring and summer.

Three TP08 heated NPs from Hukseflux were positioned on a polyethylene post at heights above the ground of 7, 17 and 27 cm in July 2013. These heights were chosen somewhat arbitrarily before the snowpack structure could be observed. In July 2014 the TP08 needles were lowered to 2, 12 and 22 cm because we had realized during a field trip in May 2014 that the lowermost depth hoar layer could be thinner than 7 cm. On another nearby post, thermistors were placed at heights of 2, 7, 17, 27 and 37 cm. Heights intermediate between the TP08 heights allow the calculation of heat fluxes, using thermal conductivity and temperature values. Unfortunately, the cables of the thermistors at 7, 27 and 37 cm, although protected, were chewed by a fox in late summer 2014 and could only be replaced the following summer. In the ground, we also placed a TP08 NP at a depth of 10 cm with two thermistors at depths of 4.5 and 13.5 cm. In the immediate vicinity of the thermistors post, we placed 5TM sensors from Decagon to monitor ground temperature and volumetric liquid water content at depths of 2, 5, 10 and 15 cm. Water content sensors used the manufacturer's calibration for mineral soils and were not recalibrated, which may produce an error of up to 3%. At that time, it was not possible to place deeper sensors because of the limited thaw depth. A few meters from these snow and ground instruments, we installed meteorological instruments to measure atmospheric variables including air temperature and relative humidity with a HC2S3 sensor from Rotronic, wind speed with a cup anemometer, both at 2.3 m height, snow height with a SR50A acoustic snow height gauge (Campbell Scientific), an IR120 infrared surface temperature sensor and a CNR4 radiometer with a CNF4 heating/ventilating system from Kipp & Zonen which measured downwelling and upwelling shortwave and longwave radiation. Heating and ventilating radiometers is mandatory to limit snow accumulation and the build-up of frost and freezing rain. Heating and ventilation were performed for 5 minutes every hour prior to measurements. This protocol of instrumentation and measurement is similar to that employed near Umiujaq (Domine et al., 2015) and were operated in the same manner with a CR1000 data logger (Campbell Scientific). Briefly, hourly measurements were recorded, except for the TP08 needles, whose operation is described in the next section.

2.2 Thermal conductivity measurements

The NP method has been used extensively for soils for a long time (Devries, 1952). (Sturm and Johnson, 1992) and (Morin et al., 2010) discussed in detail the heated NP method in snow. The automatic operation of the TP08 needles in Arctic snow and the data analysis have been detailed in (Domine et al., 2015) and only a brief summary will be given here.

For a measurement cycle, the 10 cm-long needles were heated at constant power (0.4 W m^{-1}) for 150 s. The temperature was monitored by a thermocouple at the center of the heated zone. Heat loss is a function of the thermal conductivity of the medium. A plot of the thermocouple temperature as a function of $\ln(t)$, where t is time, theoretically yields a linear curve after an initiation period of 10 to 20 s. The slope of the linear part is inversely proportional to the thermal conductivity of the medium.

In snow, NPs in fact measures an effective thermal conductivity, k_{snow} , with contributions from conductive heat transfer through the network of interconnected ice crystals and through the interstitial air, and also heat transfer due to latent heat

115 exchanges caused by water molecules sublimation and condensation generated by the temperature gradient around the heated NP (Calonne et al., 2011; Sturm et al., 1997). The variable k_{snow} is defined as:

$$F = -k_{snow} \frac{dT}{dz} \quad (1),$$

with dT/dz the vertical temperature gradient through the layer, in $K m^{-1}$, and F the heat flux in $W m^{-2}$.

120 The automatic routine developed by (Domine et al., 2015) was used to obtain k_{snow} from the heating curve. Essentially, that routine detects possible non-linearity in the heating curve and selects the most linear curve section to determine k_{snow} . The main cause of non-linearity is the occurrence of convection in the snow, which, by adding an extra heat transfer process, reduces the rate of temperature rise. This readily happens in depth hoar after 50 to 60 s of heating because of its high permeability. Since convective heat transfer is not an intrinsic snow property because it depends among other things on the heating power, it has to be detected and data affected by it must be discarded. Therefore, while for heating curves not 125 perturbed by convection, the 40-100 s heating time range was used to derive k_{snow} , the range 20-50 s was used when convection was present (Domine et al., 2015). Other causes of non-linearity include non-homogeneous snow and melting due to excessive heating. To avoid melting, automatic measurements were started only if the snow temperature was $<-2^{\circ}C$. Factors such as non-homogeneous snow may result in poor quality heating curves, which were discarded. Thermal conductivity measurements were performed once every 2 days, to take into account the slow evolution of this variable and to 130 minimize thermal perturbation to the snow. Measurements were performed at 5:00 to minimize the risk of having warm snow. The NP heating sequence takes place regardless of whether the NP is covered by snow or not. The k_{snow} data that we determined took place in air were discarded. When an NP is not snow-covered, even a slight wind produces an erratic heating curve. Should there be very little wind, snow height measurement, the value of k_{snow} , and the presence of convection often allows the detection of a non-covered probes. Incorrect or uncertain determination of NP snow coverage is nevertheless still 135 possible, and this will be discussed when relevant.

Measurements of soil thermal conductivity k_{soil} were not performed by (Domine et al., 2015), and details are therefore given here. Since snow and soil NPs are all multiplexed onto the same data logger, the same heating power had to be used in snow and soil. The thermal conductivity of soils, especially when frozen, can be much greater than that of snow (Penner, 1970), so that heating by the NP can be much lower, resulting in more noise in the heating curves. NPs do not induce convection in 140 soils because of their low permeability so that heating curves were always linear. The 30-90 s heating time range was thus used. A quality threshold based on the determination coefficient of the curve was used and curves with $R^2 < 0.75$ were discarded.

Measuring thermal conductivity in porous granular media such as snow has been suspected of presenting biases and/or systematic errors (Calonne et al., 2011; Riche and Schneebeli, 2013) and these have been discussed by (Domine et al., 2015). 145 One concern is that the relevant metric for heat exchanges between the ground and the atmosphere through the snow is the vertical heat flux. Snow is anisotropic (Calonne et al., 2011; Riche and Schneebeli, 2013) and NPs measure a mixture of vertical and horizontal heat fluxes. Anisotropy depends on snow type, with for example depth hoar being more conductive in the vertical direction and wind slabs in the horizontal direction. Moreover, a systematic error caused by the granular nature of snow was invoked by (Riche and Schneebeli, 2013). (Domine et al., 2015) discussed the impact of these processes on the accuracy of k_{snow} measurement with NPs and concluded that if the snow type was not known, the maximum error was 150 typically 29%. The largest contributions to error were the systematic error due to the use of the NP (20%) and error due to anisotropy (20%). The total error is the square root of the sum of the squares of all contributions. If the snow type is known, corrections for anisotropy and systematic bias are possible, potentially reducing errors to 10 to 20%. Such corrections were not, however, performed by (Domine et al., 2015). Given that k_{snow} varies between 0.025 and 0.7 $W m^{-1} K^{-1}$, errors due to the use of NPs are quite acceptable and measurements using NPs still very useful. Alternative k_{snow} measurement methods, i.e. 155 heat flux plates and calculations based on tomographic images, although potentially more accurate, are clearly impractical for

season-long monitoring in remote and inaccessible high Arctic sites because they require sampling and complex instruments. For soils, the issues raised by (Riche and Schneebeli, 2013) are expected to have no impact because soils are much denser with smaller grains, and are closer to a homogeneous medium at the scale of a NP. Anisotropy may however be an issue in some soil types, but we have not developed this aspect here. Based on the quality of our soil heating curves, we estimate that the error on k_{soil} is 15% or less when the soil is not frozen and 25% when it is frozen, because higher k_{soil} means lower heating by the NP and therefore less accurate heating curves.

Field measurements of snow k_{snow} and soil k_{soil} were also performed during field campaigns in spring 2014 and 2015 and summer 2013, 2014 and 2015 with a TP02 NP. Additional spring field measurements included snow density with a 100 cm³, 3-cm high box cutter, snow temperature and snow specific surface area (SSA) with the DUFISSS instrument based on infrared reflectance at 1310 nm (Gallet et al., 2009). SSA is the surface area per mass and is thus inversely proportional to snow grain size. SSA can be used to evaluate the intensity of metamorphism, as intense metamorphism driven by high temperature gradients lead to rapid grain growth and hence SSA decrease (Taillandier et al., 2007). Some of these snow measurements have been detailed by (Domine et al., 2016). Additional summer measurement included soil volume water content using an EC5 sensor from Decagon.

2.3 Soil granulometric analysis

Soil grain size distribution is useful to understand its physical properties. Samples were taken from our instrumented site at 10 cm depth in July 2015. Particle size distribution was measured with a Horiba partica LA-950V2 laser scattering particle size analyser, which used a 2-wavelength optical system, 405 and 650 nm. Five subsamples were analyzed and averaged.

2.43 Snow physics modelling

We used the Crocus model (Vionnet et al., 2012) to simulate snow physical properties. We in fact used the simulations already described in (Domine et al., 2016) for our Bylot Island site, but analyzed different output data. Very briefly, the model was forced with our meteorological data. When data were missing, ERA-interim reanalysis data were used (Dee et al., 2011), corrected following the procedure of (Vuichard and Papale, 2015) to minimize the bias between measured and ERA data. Snow thermal conductivity is calculated from the equation of (Yen, 1981), based on a correlation between density and thermal conductivity.

3 Results

The winter 2013-2014 was a low snow year so that two out of three NPs were not covered. Data are more complete for the following year and we therefore start with data from the 2014-2015 season.

3.1 2014-2015 season

Describing the structure and physical properties of the snowpack at Bylot Island helps in understanding the monitoring data. Observations made on 12 May 2015 close to our monitoring site are shown in Figure 2. Vegetation was observed to be mostly flattened by snow, with some sedge or graminoids stems still upright, but they did not seem to have impacted snow structure. We observed a basal depth hoar layer 8 to 10 cm thick, overlaid by a wind slab 11 to 12 cm thick, with in-between a thin layer of faceting crystals. Above the wind slab were thin layers of small rounded grains, decomposing precipitation crystals and a thin wind crust. The depth hoar layer was divided into two sublayers. The lower sublayer was slightly indurated and harder, although hardness and other properties appeared spatially very variable. Indurated depth hoar is a snow type seldom mentioned, as it does not form in Alpine or temperate snow, and it is not described in the international snow

classification (Fierz et al., 2009). It has been observed in the Arctic without being named for decades. Its most detailed description is probably that of (Derksen et al., 2009): "Wind slabs formed in early winter often completely metamorphose into depth hoar by the end of the season as a result of these temperature gradients [...]. The grains in these layers will be morphologically similar to regular depth hoar, but the layers will be stronger and more cohesive than normal for depth hoar layers, a relict feature of the original wind slab. We call these layers indurated." (Domine et al., 2016) gave complementary details: "Indurated depth hoar [...] forms in dense wind slabs under very high temperature gradients not encountered in Alpine snow. Its density can exceed 400 kg m^{-3} . Large depth hoar crystals coexist with small grains that have not been subject to fast crystal growth, probably because water vapour vertical transfer has followed preferential paths in the dense snow. This often gives indurated depth hoar a milky aspect. Unlike typical depth hoar (e.g. taiga depth hoar, [...]) which has a very low cohesion, indurated depth hoar is reasonably cohesive, although fairly brittle, and large blocks can easily be cut out of it and manipulated."

The indurated depth hoar ~~at~~ here showed signs of early season melting in the form of rounded grains that were partially to almost totally transformed into depth hoar, but bonds were stronger than for regular depth hoar. The indurated depth hoar that forms in refrozen snow is slightly different from that observed in wind slabs, in that no small grains are present and it does not have a milky aspect. In line with (Domine et al., 2016), we represent this type of depth hoar with a symbol that does not exist in the classification of (Fierz et al., 2009), as that classification is ideal for Alpine snow but is not detailed enough to represent many Arctic snow types. The depth hoar upper sublayer was very soft, appeared more homogeneous and showed no signs of melting. Vertical profiles of density, SSA and thermal conductivity are also shown in Figure 32. Several density measurements were made in the lower depth hoar layer, yielding values between 172 and 260 kg m^{-3} . In comparison, the upper depth hoar layer was at 170 kg m^{-3} , a rather low value for depth hoar. The vertical profiles of the three measured physical variables reflect the observed stratigraphy rather well, with higher values of all three variables for the wind slab and lower values for the depth hoar, as already noted by (Domine et al., 2016). The basal snow temperature was -17.1°C .

Figure 3 shows time series for k_{snow} , as well as snow temperature, air temperature, wind speed and snow height. Snow height is spatially very variable in the Arctic at the 50 cm scale, mostly because of wind effects and of microtopography. Typically, in May around our site, snow height varied between 22 and 45 cm within 5 m. Measurements using an avalanche probe at 236 spots within 200 m of our site on 12 May 2015 showed a mean snow height of 25.3 cm, with a standard deviation of 13.1 cm (Domine et al., 2016). Therefore, snow height given by our acoustic snow gauge can only be taken as an indication of the actual snow height at the very NP site, about 5 m away. On 12 May 2015, snow height was 27 cm at the pit shown in Figure 2, 50 cm from the NP post, while the snow gauge indicated 35 cm.

The lowest NP, at 2 cm, was covered by the first snow fall on 12 September 2014. That initial snow partially melted and the first data point that was almost certainly obtained in snow was on 24 September. After initial values around $0.04 \text{ W m}^{-1} \text{ K}^{-1}$, k_{snow} dropped to values around $0.02 \text{ W m}^{-1} \text{ K}^{-1}$ because of rapid depth hoar formation. These values may seem a bit low, especially considering that air has a thermal conductivity of $0.023 \text{ W m}^{-1} \text{ K}^{-1}$, but the low value can be attributed to a negative systematic error of about 20% caused by the NP method, as described in (Riche and Schneebeli, 2013) and discussed above.

It is fairly certain that this NP was not in an air gap, because measurements in air almost always produce erratic heating curves due to complex convection, and none of the heating curves were suspicious. Another reason for the low value is that ~~that~~ Furthermore, depth hoar is probably the most anisotropic snow, with the vertical component of thermal conductivity being the greatest one (Calonne et al., 2011; Riche and Schneebeli, 2013). Since we measure a mixture of both vertical and horizontal component, the value is necessarily lower than the vertical component, ~~to that~~ Taking into account all error sources, the actual vertical component is probably 25 to 30% greater than the value obtained from the NP.

The NP at 12 cm may have been in snow on 1 November, but this is uncertain. On 10 to 11 November, the strongest wind storm of the winter, which reached wind speeds of 12.9 m s^{-1} , appears to have formed a wind slab that buried the 12 cm NP, which recorded a k_{snow} value of $0.28 \text{ W m}^{-1} \text{ K}^{-1}$. The k_{snow} value at 12 cm remained close to that value until 28 March. Until 1

January, data are noisy, possibly because the NP was close to the snow surface and therefore subject to air advection by wind, which, by adding a heat loss process, produced randomly a slight positive artifact. The 12 cm k_{snow} value then dropped to 0.23 W m⁻¹ K⁻¹ on 30 March, while no special meteorological event was recorded by the wind and temperature sensors. Between 27 and 30 March, the wind remained under 4 m s⁻¹ and the temperature showed regular diurnal cycles between -40 and -20°C. The value of k_{snow} started rising steadily on 5 May to reach a value of 0.33 W m⁻¹ K⁻¹ on 29 May. Considerations of the evolution of metamorphic conditions in the snowpack, discussed subsequently, are required to explain this process.

The NP at 22 cm was definitely covered by snow on 21 January 2015. The value remained around 0.06 until 8 February, indicating that it remained as undisturbed precipitation. On that date, a moderate wind storm started, reaching 5.6 m s⁻¹ at 11:00. The resulting wind slab had k_{snow} = 0.175 W m⁻¹ K⁻¹, increasing steadily to 0.25 W m⁻¹ K⁻¹ on 23 April, most likely because of slow sintering. On 25 April, the value rose to 0.309 W m⁻¹ K⁻¹, but this is related to no wind event. On 17 April, a 44 h-long wind event culminating at 6.8 m s⁻¹ did not produce any rise in k_{snow} , indicating that the 22 cm needle was sufficiently covered to be unaffected by wind. Air temperature was no different from other nearby days. The heating curve is slightly curved, which could have been caused by an unsteady heating current. In any case, we attribute this short temporary rise to noise in the data. Except for this rise, k_{snow} stabilized around 0.26 W m⁻¹ K⁻¹ until the end of May, which we will discuss subsequently in light of metamorphic conditions.

Three soil pits were dug in the summer 2013 to 2015 down to the thaw front in the polygon where our instruments are located to measure soil physical properties and another two pits were dug just for observations. An organic litter layer 3.5 to 6 cm thick was observed. Lower down was a layer of organic-rich silt-looking material-clay was observed. Figure 4 shows vertical profile of soil temperature, thermal conductivity, k_{soil} , and volume water content fraction. The general trend is an increase of k_{soil} with depth, while temperature expectedly decreases. Soil grain size distribution was obtained from 5 samples taken around 10 cm depth. The average data show a bimodal size distribution with modes centered at 17 and 59 μm. If the standard 50 μm size limit between sand and silt is used, then our sample is 65% silt and 35% sand by mass, so that the soil here is a mixture of silt and fine sand.

Figure 5 shows the evolution of the k_{soil} and temperature measured every other day by the NP at 10 cm depth between 28 July 2014 and 26 June 2015. Figure 5 also shows hourly soil temperature and volume water content at 10 cm depth measured by a 5TM probe located about 1 m away. Both temperature measurements show similar variations, but the 5TM is 1 to 2°C warmer, in part due to a positive 0.5°C offset on the 5TM. The soil temperature reached 0°C on 9 September and stayed at that temperature without significant freezing, as indicated by the water content, until 27 September. The soil water freezing continued until 10 October, at which point only water in small pores remained liquid. Until 30 September 2014, the soil thermal conductivity stayed constant with k_{soil} = 0.73 W m⁻¹ K⁻¹, with a standard deviation of 0.02 W m⁻¹ K⁻¹, while the soil volume water content was 49.5±1.3%. Except for very low water contents, soil freezing is expected to manifest itself in an increase in k_{soil} , (Inaba, 1983; Penner, 1970) because ice has a much higher thermal conductivity than water (2.22 vs. 0.56 W m⁻¹ K⁻¹ at 0°C). Measurements of k_{soil} shows detectable soil freezing between 30 September and 2 October, with k_{soil} increasing from 0.76 to 1.16 W m⁻¹ K⁻¹. The value of k_{soil} then rapidly increased to 1.8 W m⁻¹ K⁻¹ on 10 October, confirming 5TM data that the soil was then almost essentially frozen at 10 cm depth, except for water in small pores (Inaba, 1983; Penner, 1970). The average and standard deviation of k_{soil} then were 1.95 ± 0.20 W m⁻¹ K⁻¹ for the winter season. The large standard deviation only indicates the greater uncertainty of our instrument for high k_{soil} values, because NP heating is less pronounced. The values of both unfrozen and frozen soil are consistent with those expected from a fine grain mineral material mixed with organic matter (Kujala et al., 2008; Penner, 1970). Even as the soil temperature decreases to -30°C, no further increase in k_{soil} is observed, suggesting that essentially all the water that can was already frozen on 10 October. The value of k_{soil} then only decreased, and did so in just a few days, when thawing took place on 20 June 2015 and k_{soil} returned to its previous thawed value. Figure 5 shows that the increase in k_{soil} upon freezing actually takes place after the initiation of freezing and that its decrease in spring is complete before full thawing. In the case measured here, a small ice fraction

produces a value of k_{soil} as if all the water was liquid.

3.2 2013-2014 season

Figure 6 shows the value of k_{snow} at a height of 7 cm for the 2013-2014 season, as only that NP was sufficiently covered to give reliable data. As previously, we also show snow temperature and height, wind speed and air temperature. That season, the snow height at our snow gauge was noticeably lower than at our NP post. On 14 May 2014, the gauge indicated 13 cm, while there was 18 cm of snow at the NP post. Measurements using an avalanche probe at 314 spots within 200 m of our site on 14 May 2015 showed a mean snow height of 16.2 cm, with a standard deviation of 13.7 cm (Domine et al., 2016).

The snow stratigraphy was observed on 14 May 2014 about 50 cm from the NP post and vertical profiles of density, specific surface area and thermal conductivity were measured and are shown in Figure 7. The stratigraphy was spatially extremely variable and complex with frequent alternation of hard and soft layers. The basal layer of columnar depth hoar was very soft and collapsed at the slightest contact so that we were not able to measure its density. Gaps in the basal layer were frequent, indicating that it had collapsed naturally in many places. These spontaneous collapse features cannot be mistaken for lemming burrows (Figure 8). This very soft and fragile structure was most likely due to the loss of matter caused by the upward water vapor flux generated by the temperature gradient in the snowpack. Such basal depth hoar collapse in the low and high Arctic have already been described by (Domine et al., 2015) and (Domine et al., 2016). Above the basal depth hoar was a layer of indurated depth hoar formed by the metamorphism of a hard wind slab into depth hoar, as ~~already described by (Domine et al., 2012) detailed above. Depth hoar crystals can indeed grow within dense wind slabs when a large temperature gradient persists. Indurated depth hoar formed in a wind slab is different from depth hoar formed e.g. in low density fresh snow. In such indurated depth hoar, areas with small grains remain, giving the depth hoar a milky aspect.~~ Although brittle, the indurated depth hoar observed was fairly solid and could readily be sampled without damaging its structure. It has a high thermal conductivity ($0.37 \text{ W m}^{-1} \text{ K}^{-1}$), high density (383 kg m^{-3}) and a SSA (14.6 to $19.6 \text{ m}^2 \text{ kg}^{-1}$) slightly lower than most wind slabs but higher than typical depth hoar. No symbol for indurated depth hoar formed in wind slabs exists in the classification of (Fierz et al., 2009). ~~because indurated depth hoar can probably never form in Alpine snow, so we propose an appropriate symbol here~~ (Hall et al., 1991) used open squares for “solid-type depth hoar”, presumably indurated depth hoar. (Sturm et al., 2002) used a mixtures of wind slab and depth hoar symbols for “wind slab to depth hoar” presumably also indurated depth hoar. These examples show that the need for a specific indurated depth hoar symbol exists. Since the symbol we proposed earlier for indurated depth hoar formed in refrozen snow consists of a depth hoar symbol with a large open circle, we propose to use a depth hoar symbol with a dot (the fine grain symbol) for indurated symbol formed in wind slabs.

The intermediate layer of faceted crystals around 10 cm indicates an extended period of low wind weather, during which temperature gradient metamorphism could proceed without perturbation by any wind compaction episode. Few precipitation events took place that winter, as indicated by the small amount of snow observed in May 2014. The snow gauge (Figure 6) also indicates little precipitation, although many wind-erosion episodes at our gauge spot limit our ability to evaluate precipitation in 2013-2014.

Snow cover in 2013 started late, on 12 October. Our NP at 7 cm recorded a first significant k_{snow} increase, from 0.050 to 0.094, between 7 and 9 November, and we attribute this to a wind event that lasted about 14 hours on 7 November, with wind speed reaching 7 m s^{-1} , and which must have formed a wind slab of moderate density and thermal conductivity around $0.1 \text{ W m}^{-1} \text{ K}^{-1}$, which remained stable for a few days before increasing to $0.178 \text{ W m}^{-1} \text{ K}^{-1}$ between 17 and 21 November. This is well correlated to 2 consecutive wind events, each lasting over 24 hours on 18 and 21 November, and which respectively reached 8.8 and 9.4 m s^{-1} . We propose that erosion and redeposition of snow took place, leading to the formation of a denser layer that rapidly sintered. On 23 November, k_{snow} decreased to $0.077 \text{ W m}^{-1} \text{ K}^{-1}$, which we attribute to wind erosion and subsequent redeposition of softer snow of low k_{snow} , as the 21 November storm lasted until noon, while the measurement took place at 5:00. The next observed rise in k_{snow} was on 3 December to 0.156 and then to $0.192 \text{ W m}^{-1} \text{ K}^{-1}$ on 5 December. The

Rise between 29 November and 3 December was caused by a 48 hour wind storm that reached 9.3 m s^{-1} , making the 1 December heating plot unreliable. The subsequent rise is attributed to another storm on 2-3 December that reached 8.1 m s^{-1} . Variations in k_{snow} were thereafter small. The NP was certainly buried several cm below the surface and little more affected directly by wind. Factors which can affect the value of k_{snow} include temperature, through its effect on the thermal conductivity of ice (which increases as temperature decreases), wind which through wind pumping may add another heat transfer process and produce a positive artefact on k_{snow} , changes in snow structure due to metamorphism, and simply noise in the data. Deconvolution of all these effects, given their small impact and the presence of noise in the data, appears of little interest. It is nevertheless noteworthy that the drop from 0.238 to $0.193 \text{ W m}^{-1} \text{ K}^{-1}$ on 8 March coincides with a wind event on 7 March (6.2 m s^{-1}). We speculate that this may have caused wind pumping leading to sublimation, mass loss and a drop in k_{snow} .

On 14 May 2014, we excavated the snow around the NPs, essentially ending our time series. A photograph of the snow profile is shown in Figure 9. The NP at 7 cm was in an indurated depth hoar layer, but very close to the border with a thin depth hoar layer. Above that was a layer of faceted crystals/depth hoar. Given the stratigraphy, the 7 cm NP had been completely buried for months and changes in k_{snow} for the past few months cannot be interpreted in terms of precipitation/erosion processes.

Figure 10 shows soil data for the 2013-2014 season. Before the initiation of freezing, the soil volume water content at 10 cm depth was $56.6 \pm 0.8\%$. The soil temperature at 10 cm depth reached 0°C on 6 September. Freezing was very slow until 12 September, when the water content started showing a detectable decrease. Most of the water was frozen on 1 October and the temperature started to drop. Until 20 September, k_{soil} was essentially constant, with $k_{\text{soil}} = 0.71 \pm 0.04 \text{ W m}^{-1} \text{ K}^{-1}$. This is not significantly different from the following season, while the volume water content is slightly larger (56.6 vs. 49.5%). Again, here a small ice fraction does not seem to affect the value of k_{soil} , which remained similar to that in fully thawed conditions.

4 Discussion

4.1 Snow metamorphism and water vapor fluxes

The snowpack structure observed at Bylot Island, especially in 2015, is frequently encountered on Arctic tundra (Benson et al., 1993; Derksen et al., 2009; Domine et al., 2002; Sturm and Benson, 2004), especially in areas of moderate wind, and mostly consists of a lower depth hoar layer and an upper wind slab. The depth hoar layer forms because of the elevated temperature gradient at the beginning of the season. Figure 11 shows the temperature gradients in the 2-12 cm and 12-22 cm snow height ranges, as obtained from the NPs temperature measurements every other day at 5:00. Higher time resolution measurements would have been desirable, but most of the thermistors that logged temperature every hour were damaged by a fox. Figure 11 nevertheless shows that NP data are similar to the gradient derived from thermistor data at 2 and 17 cm, so that reasoning on NP data is still adequate. Values barely reach 100 K m^{-1} , while other Arctic or subarctic locations showed early season values in the $200\text{-}300 \text{ K m}^{-1}$ range (Sturm and Benson, 1997; Taillandier et al., 2006). Reasons for the lower values reported here include: (i) we only obtained values starting on 1 November because our thermistor at 7 cm did not function and we had to wait for the 12 cm NP to be covered to obtain data. Early season values, when the snowpack was thinner and the ground not completely frozen, were almost certainly higher; (ii) sites with higher gradients were inland sites and atmospheric cooling was faster, reaching -35°C in November (Taillandier et al., 2006). Here, the presence of the sea and the latent heat released by sea water freezing led to a much slower and gradual cooling, as shown in Figures 3 and 6. Figure 11 shows that the temperature gradient in both height ranges are pretty similar until 17 March. Between 15 and 17 March, the air temperature rose from -37 to -10.5°C (Figure 3), and that brutal and irreversible warming dramatically changed the thermal regime of the snowpack, as seen in Figure 11, where the gradient in the upper regions suddenly becomes much greater than in

365 the lower one.

With regards to metamorphism, the actual variable of interest is the water vapor flux, rather than just the temperature gradient. This flux is the product of the diffusion coefficient of water vapor in snow, D_v , by the water vapor concentration gradient. D_v as reported by (Calonne et al., 2014) depends on snow density and we estimate that it was $2 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ below 12 cm height because of the presence of depth hoar and $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ between 12 and 22 cm, where wind slabs prevail. Using
370 known values of ~~its computation requires the knowledge of snow diffusivity, which we did not measure, so we will consider instead the water vapor gradient. This has been calculated (Figure 12) using the temperature data and~~ the water vapor pressures over ice (Marti and Mauersberger, 1993), we computed the fluxes shown in Figure 12. Between 2 and 12 cm, the flux decreases exponentially over time due to snow cooling and the exponential dependence of vapor pressure on temperature. On December 1st, flux values have decreased to less than a quarter of their November 1st values. This is when
375 the snow height increased from 10 to 18 cm (Figure 3) and based on Figure 2 and other pit observations, when deposited snow stopped transforming into depth hoar. The transition from depth hoar to wind slab in Arctic snowpack is almost always very abrupt, so that there is certainly a threshold effect, as already indicated by previous studies (Marbouty, 1980). Given the discontinuous nature of precipitation and snow accumulation (where wind plays a key role), these data suggest that at some point in the season, a snow accumulation episode (whether caused by precipitation or wind) will decrease the temperature
380 gradient and hence the water vapor flux below the threshold triggering the depth hoar to wind slab abrupt transition.
It is interesting to evaluate whether calculated fluxes can explain the mass loss leading to snow collapse. Assuming all the flux comes from a 5 cm-thick depth hoar layer of density 250 kg m^{-3} , this represents 12.5 kg m^{-2} of depth hoar. Assuming early season fluxes reached $0.5 \text{ mg m}^{-2} \text{ s}^{-1}$ by extrapolating the data of Figure 12, this leads to a mass loss of 2.6 kg m^{-2} of depth hoar over 2 months, insufficient to explain the near-total disappearance of the depth hoar in some places, so that
385 processes other than purely diffusive fluxes must have been operating. Convection-enhanced fluxes is a possibility, as these may have taken place in the highly permeable depth hoar that formed very early in the season, as evidenced by our thermal conductivity measurements (Figure 3). (Sturm and Johnson, 1991) did observe such convection in depth hoar, and the irregular nature of collapse (Figure 8) is compatible with the presence of convection cells. Another possible factor is wind-induced air advection. Wind-pumping was indeed favored by the rough snow surface, the nearly continuous wind in the early
390 season in both years studied (Figures 3 and 6) and the shallow and highly permeable snowpack. Finally, these estimates are based on the D_v values measured by (Calonne et al., 2011), who, based on details given, do not seem to have studied large-grain depth hoar as found in the Arctic. It cannot be ruled out that vapor diffusion enhancement by the sublimation-condensation cycles (Sturm and Benson, 1997) does not take place in Arctic depth hoar. (Sturm and Benson, 1997) found an average enhancement factor of 4, and if such a factor applied to our case, it would explain the near complete disappearance
395 of the basal depth hoar.
Figure 12 shows that ~~The highest values are observed at the beginning of the season when the ground was still warm, and the strong upward vapor flux is responsible for depth hoar growth. In~~ the upper region, the water vapor flux was much lower and apparently insufficient ~~pressure gradient does not appear to have been high enough~~ to allow depth hoar formation. ~~Figure 12 shows that for~~ most of the snow season, there was a continuous upward water vapor flux, leading to overall water vapor
400 loss to the atmosphere. The late season reversal of the flux direction in early May lasted only about a month and was insufficient to reverse the overall loss trend. ~~It is interesting that t~~ This reversal coincides with the change in the trend of evolution of k_{snow} at 12 and 22 cm. At 12 cm, k_{snow} started to rise and at 22 cm k_{snow} stopped rising at that moment. We propose that at 12 cm, the water vapor ~~gradient flux~~ led to a density increase and enhanced sintering caused by the growth of bonds between grains under the low temperature gradient conditions (Colbeck, 1998), resulting in a k_{snow} increase. At 22 cm
405 on the other hand, the snow became warmer than the other layers (Figure 3), so that the dominant process switched from condensation to sublimation, leading to a density decrease, halting the rise in k_{snow} or perhaps even producing a slight decrease.

There is also a temperature gradient, and hence a water vapor flux, between the soil and the snow, as already mentioned by (Sturm and Benson, 1997) from observations in interior Alaska. The resulting soil water vapor loss is detectable in Figure 10. In late summer 2013, the liquid water content in the soil at 10 cm depth was about 58%. After thawing in early July 2014, the water content only rises back to 31% meaning that almost half of the water present in the soil the previous summer has been lost by sublimation during the snow season. If this value applies to the top 10 cm of the soil, then it lost 17 kg m⁻² of water, the same order of magnitude as observed by (Sturm and Benson, 1997), 5 kg m⁻². Within a few weeks, the water content had risen back to 47% because of precipitation in July 2014. At 2 and 5 cm depth, the loss appears even greater, but the signal is not as simple, as erratic water percolation due to snowmelt is superimposed onto the thawing signal. ~~The depth hoar collapse mentioned above is another indication of the large surface to atmosphere water loss during most of the year in the high Arctic.~~

4.2 Snowpack structure and subnivean life

The presence of a soft depth hoar layer clearly facilitates subnivean travel and food search. The softer the layer, the easier the travel and presumably the better the feeding and reproductive success of subnivean species. Factors that adversely affect the softness of this layer include wind packing and melt-freeze events. Wind storms form hard dense wind slabs. At the base of the snowpack, the strength of the gradient may allow their transformation into indurated depth hoar, but such depth hoar is much harder than that formed in softer snow (Domine et al., 2012). Likewise, early season melt freeze events may lead to ice formation. However, in the Arctic, melt-freeze crusts can transform into depth hoar (Domine et al., 2009). This is probably what happened in autumn 2014, as signs of early season melt-freeze cycling were still observable in May 2015 (Figure 3). Based on these observations, it appears that feeding conditions for subnivean species may have been slightly better in 2013-2014 than in 2014-2015. However, at this stage the evidence is tenuous, and mostly based on spring observations. Thermal conductivity monitoring does not invalidate nor support this conclusion: no NP was placed low enough the first year, and the second year shows a very low value at 2 cm height, except for the first month of snow. It is likely that the higher early season values were due to the presence of a melt-freeze crust that rapidly transformed into depth hoar while the k_{snow} value decreased.

The recent work of (Fauteux et al., in press) however appears consistent with our observations. These authors measured lemming abundances very close to our snow study site right after snow melt in the natural environment and in a very large 9 ha enclosure to minimize predators impact on populations. The enclosure data is therefore expected to be more likely to be affected mostly by just snow conditions. Their data show counts of 6 lemmings ha⁻¹ in June 2014 vs. 2 lemmings ha⁻¹ in June 2015, in agreement with our field observations. This correlation is of course very preliminary and only serves to illustrate the interest of monitoring snow conditions to understand lemming population dynamics.

4.3 Measurements vs. simulations of snow k_{snow}

Our time series of k_{snow} allow us to test the ability of a detailed snow physics model to predict the value of this variable. This test is important, as the water vapor flux is an important process in the shaping of Arctic snowpacks. Giving that detailed snow physics models such as Crocus (Vionnet et al., 2012) or SNOWPACK (Fierz and Lehning, 2001) do not take into account these fluxes, their ability to predict k_{snow} needs testing. A paper on SNOWPACK (Bartelt and Lehning, 2002) states that that model does include water vapor fluxes, but the scheme described was never actually implemented in the model (C. Fierz, private communication, 2015). Figure 13 compares our measurements of k_{snow} with those simulated by Crocus. The Crocus runs performed are those detailed in (Domine et al., 2016) for herb tundra conditions.

It is clear that simulations and measurements yield very different results. Measurements show low values for the lower depth hoar layers and high values for the upper wind slabs. On the contrary, simulations show a value around 0.26 W m⁻¹ K⁻¹ for the

very basal layer, indicating a melt-freeze crust, values around $0.12 \text{ W m}^{-1} \text{ K}^{-1}$ for the lower depth hoar layers and values always lower than $0.07 \text{ W m}^{-1} \text{ K}^{-1}$ for the upper layers. On 13 May, high simulated values appear around 22 cm.

Our proposed interpretation of these differences, aided by a detailed analysis of Crocus output data, is as follows. Crocus simulated a melting episode in late September, giving the basal layer a high thermal conductivity. This is consistent with our observations of a melt-freeze relic in the basal depth hoar layer. However, Crocus cannot predict the transformation of a melt-freeze layer into depth hoar because it does not simulate the required vapor fluxes. These fluxes lead to mass loss in the lower layers and mass gain in the upper ones. This is an important process that contributes to the observed inverted density profiles (Figure 3) (Sturm and Benson, 1997) and hence the inverted thermal conductivity profiles because thermal conductivity is calculated from density only. The other processes that lead to dense upper layers are wind packing and to a smaller extent weight compaction. The Crocus representation of the wind-packing process cannot be evaluated here, as the density increase also has contributions from water vapor deposition due to the upward flux and their respective contributions cannot be observed separately. An appropriate description of the water vapor flux is required to test the representation of wind packing here. In any case, it is clear that omitting vapor fluxes in Arctic snowpacks leads to an inadequate simulation of the thermal conductivity profile of the snowpack.

A detailed evaluation of the ability of Crocus to reproduce the ground thermal regime is in order. However, ground temperature also depends on soil properties so that coupling to a land surface scheme is required for full testing. Crocus is currently coupled to the land surface scheme ISBA through the SURFEX interface. Improved snow and soil schemes for ISBA are being tested (Decharme et al., 2016) and the evaluation of these new schemes will be the subject of future work.

Lastly, the parameterization of (Yen, 1981) to calculate thermal conductivity from density may not be suitable for Arctic snow. For a density representative of the depth hoar studied, 200 kg m^{-3} , (Yen, 1981) predicts $k_{\text{snow}}=0.11 \text{ W m}^{-1} \text{ K}^{-1}$, while we consistently measured values around $0.025 \text{ W m}^{-1} \text{ K}^{-1}$. The more recent parameterization of (Calonne et al., 2011) predict $0.10 \text{ W m}^{-1} \text{ K}^{-1}$. Both parameterization are based on a small number of values (30 for (Calonne et al., 2011)) obtained on Alpine or temperate snows. By contrast, using the parameterization of (Sturm et al., 1997) based on over 500 values of Arctic or subarctic snows predicts $k_{\text{snow}}=0.065 \text{ W m}^{-1} \text{ K}^{-1}$. The extensive data set of (Sturm et al., 1997) also shows that for a given density value, the range of k_{snow} values varies by a factor of 4 to 5, and our measured values are within this range. These correlation-based estimated of k_{snow} show that (i) density-thermal conductivity correlations cannot accurately predict k_{snow} ; and (ii) using parameterizations based on a small data sets consisting mostly of Alpine or temperature snow cannot be used for Arctic snow.

4.4 Seasonal variations of k_{soil}

Understanding and predicting the seasonal variations of k_{soil} is essential for modelling the thermal regime of permafrost. An important issue is whether k_{soil} can be modelled using a bimodal distribution, i.e. a single value for the thawed state and a single value for the frozen state, or more time-variable values have to be used. (Goodrich, 1986) used an NP fairly similar to ours to measure the seasonal variations in k_{soil} in Canada and concluded that using a bimodal distribution could lead to large errors. (Overduin et al., 2006) monitored k_{soil} in Alaska and observed long transition periods during freezing and thawing. In autumn, the rise between the thawed and frozen values took over a month, while in the spring, complex processes were observed, in particular a spike leading to very high values at the end of the thawing period.

Here, in contrast, we find essentially a bimodal distribution, with transition periods of less than ten days. The transition from thawed to frozen k_{soil} values takes six days in 2013 and eight days in 2014 (remember that measurements are made every two days only). The transition from frozen to thawed k_{soil} values takes 2 days in 2015. In 2014, the data are not of sufficient quality to determine the transition duration accurately. The fast thawed to frozen transition cannot be explained by rapid freezing, as this takes over a month for both years studied. The transition takes place at the end of freezing, and we suggest that the k_{soil} transition can only take place when the water bridges (Sakaguchi et al., 2007) at the soil grain contacts freeze. A

significant fraction of conductive heat transfer takes place at grain contacts where water accumulates because of surface tension effects (Penner et al., 1975). These contacts are expected to freeze last because of the small thickness of the water film. Since ice has a much greater thermal conductivity than water, freezing of the contacts is expected to lead to an increase in k_{soil} . This hypothesis is comforted by the observation that the k_{soil} transition during thawing takes place at the onset of thawing, and the ice bridges at the grain contacts are here expected to thaw first.

The bimodal distribution observed here contrasts with the studies of (Goodrich, 1986) and (Overduin et al., 2006). It is likely that the duration of the transition depends on soil properties and in particular on grain size distribution and water content. Another factor that may come into play is the heating power used to measure k_{soil} . We suggest that it may lead to an artefact if it is too high. We used a power of 0.4 W m^{-1} . Neither (Goodrich, 1986) nor (Overduin et al., 2006) specify their heating power, but most researchers measuring k_{soil} with heated line sources use much higher (and arguably more suitable for obtaining quality data) powers. For example, (Sakaguchi et al., 2007) used 2.7 W m^{-1} to study sandy soils, about 7 times as large as what we used. When we measure k_{snow} in snow close to 0°C , melting can occur and this manifests itself by reduced heating, as most of the heating power is absorbed by latent rather than sensible heat. This translates into an apparent very high (and unreasonable) k_{snow} value, because k_{snow} is inversely proportional to the logarithm of the rate of heating (Morin et al., 2010). The risk of melting is of course reduced if a low heating power is used. In soils, there is a range of melting temperatures but we propose that the fraction of latent vs. sensible heat is reduced if the heating power is low. Moreover, just before the onset of thawing, a high power may induce melting, leading to an apparent k_{soil} value higher than the frozen value, as observed by (Overduin et al., 2006). Melting may also lead to water redistribution, and hence structural changes that may durably modify k_{soil} values in the vicinity of the line source. By limiting the frequency of measurements to once every 48 h and by also reducing the power, we minimize such structural changes and this maximizes the chances that our measured values are representative of those of the studied medium. Of course, we realize that this has a price: heating being reduced, the quality of the data is not as good as when higher powers are used. In any case, we cannot claim based on just these measurements that k_{soil} values can be modelled in general with a bimodal distribution. We merely provide evidence that in our case, we did observe such a distribution. In our opinion, more measurements on different soil types using different heating powers are needed to determine whether (1) the shape of the distribution depends mostly on soil type and properties or (2) non-bimodal distributions are artefacts caused by high heating powers.

5 Conclusion

We feel that the following points are important conclusions of this study:

1. Vertical water vapor fluxes induced by the temperature gradients in the soil and the snowpack strongly determine snow conditions, soil dehydration and the water budget of the surface.
2. Water vapor fluxes also determine the snow thermal conductivity profile and the ground thermal regime. The comparison of observed vs. simulated thermal conductivity profile demonstrates that omitting these fluxes lead to a radically different snow thermal conductivity profile.
3. Major snow models (Crocus, SNOWPACK) do not describe water vapor fluxes. The consequences on the water budget, on the ground thermal regime, on the energy budget of the surface, and possibly on climate may be quite significant.
4. For both years studied, a layer of soft depth hoar was present at the base of the snowpack, which seems to be favorable conditions for subnivean life. In the second year, a melt-freeze layer at the very base of the snow pack may have rendered conditions somewhat less favorable for a few weeks, but k_{snow} monitoring indicates that it transformed rapidly into depth hoar. In May 2015, however, we observed that that basal depth hoar was harder than in May 2014. We note with interest that lemming populations were also higher in spring 2014 than in spring 2015

(Fauteux et al., in press).

5. According to our data, soil thermal conductivity can be modelled using one value for the thawed period and one value for the frozen period. This is in contrast with previous studies. This may be due to different soil type and properties in different studies. Alternatively, the transition periods between thawed and frozen values may be artificially lengthened when too high heating powers are used for thermal measurements.

Supplement

Data used in Figures 3, 5, 6 and 10 are presented in a spreadsheet as a supplement to this paper.

Author contributions

F. Domine designed research. D. Sarrazin built and deployed the instruments with assistance from F. Domine. M. Barrere and F. Domine performed the field measurements. F. Domine and M. Barrere analyzed the field data. M. Barrere performed the model simulations. F. Domine prepared the manuscript with comments from M. Barrere and D. Sarrazin.

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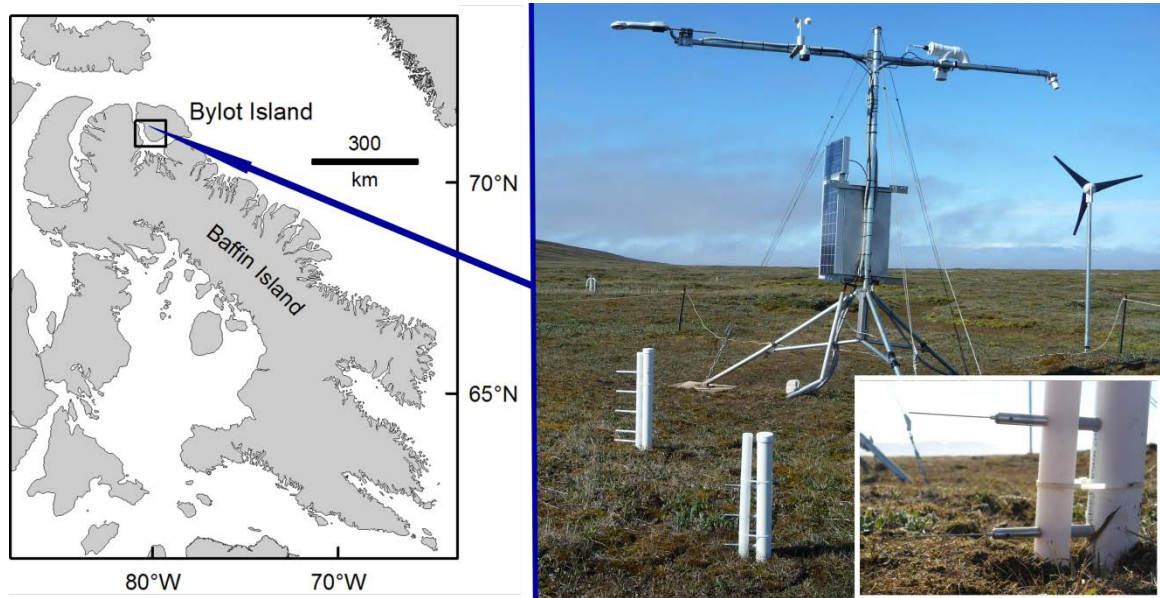
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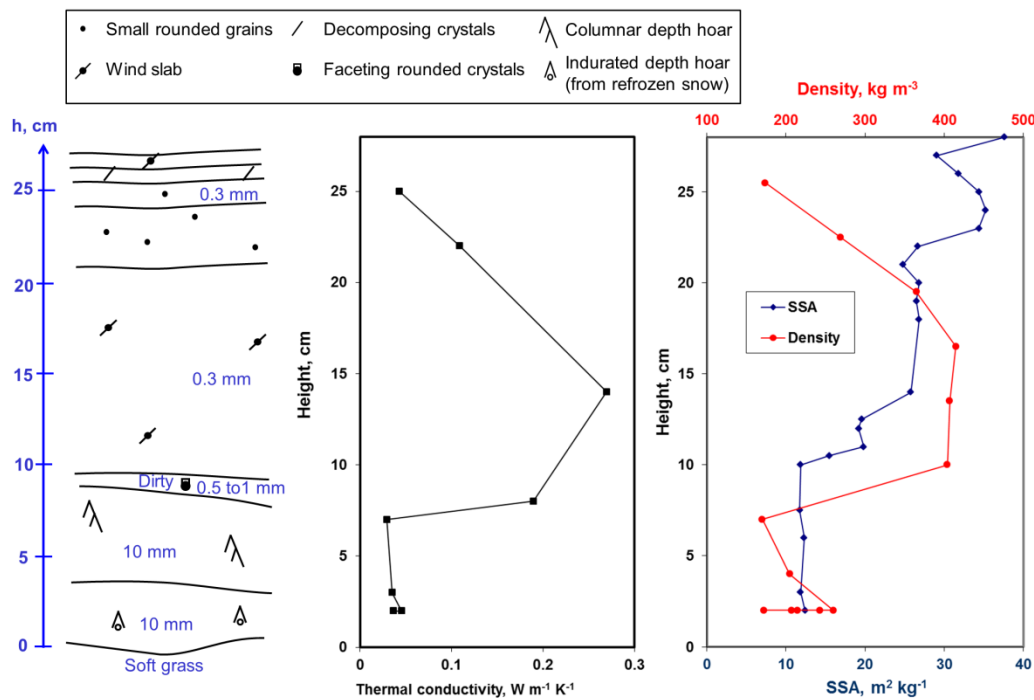
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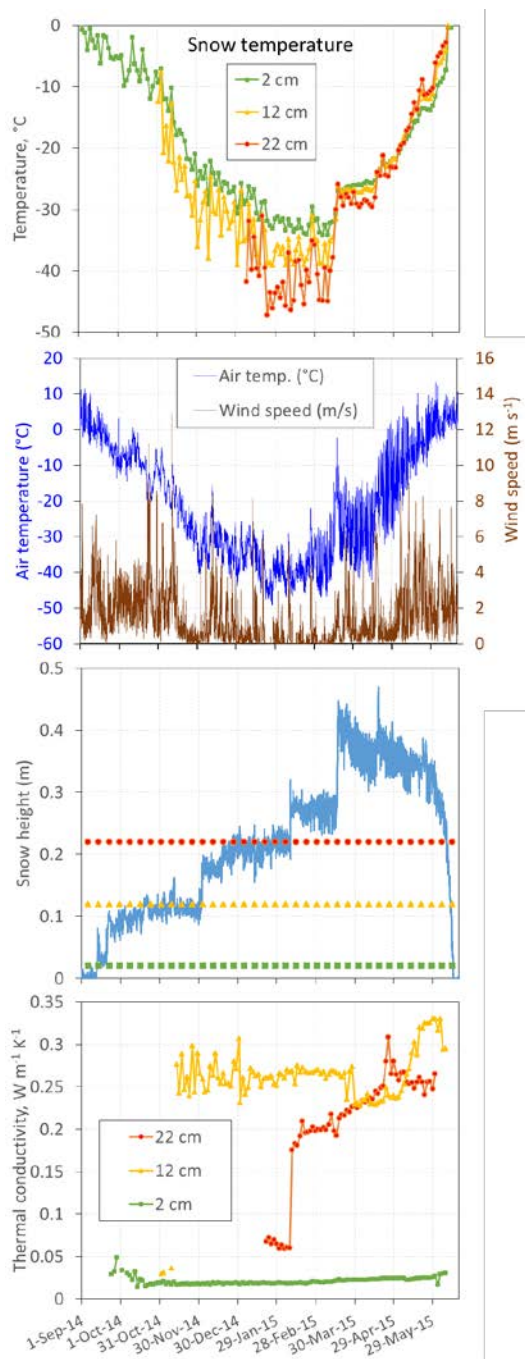
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Figure 1. Location of the study site on Bylot Island in the Canadian Arctic archipelago and photograph of the monitoring station deployed at Bylot Island. The polyethylene post with the three TP08 heated needle probes is in the foreground. The polyethylene post with the five thermistors is visible behind it. The radiometers, SR50 snow height gauge, cup anemometer, temperature and relative humidity gauge, and surface temperature sensors are visible on the tripod, from left to right. The CR1000 data loggers and batteries are in the metal box on the tripod. Batteries are recharged by a solar panel and a wind mill in winter. Inset: detail of the lower two TP08 needles after their positions were lowered in July 2014.



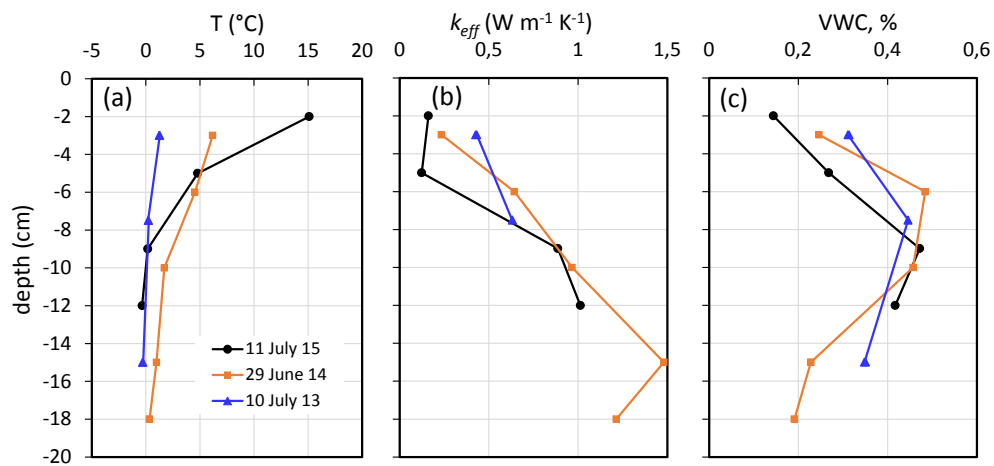
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Figure 2. Stratigraphy and vertical profiles of snow physical properties near our study site on 12 May 2015. Visual grain sizes are indicated in the stratigraphy. Density data are for the middle of the 3 cm-high sample. Snow type symbols are those of [Fierz *et al.*, 2009], except for the basal melt-freeze layer which transformed into depth hoar to form an indurated layer, as detailed in the text.

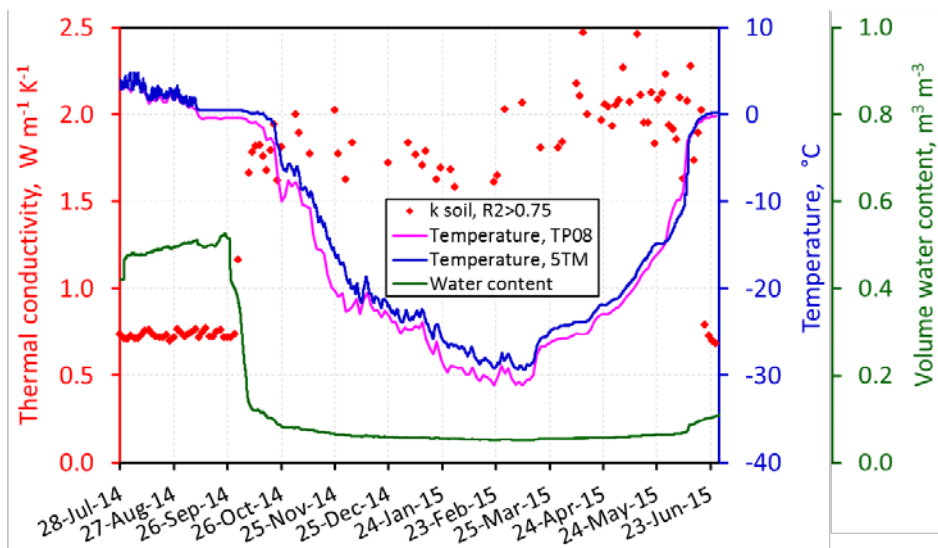


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Figure 3. Snow temperature, air temperature, wind speed, snow height and snow thermal conductivity at three heights during the 2014-2015 winter season at Bylot Island. The levels of the three thermal conductivity needle probes (NPs) are indicated in the snow height panel. Note that the snow height gauge and the NPs were about 5 m away, so that snow height between both spots may have been different. Snow temperatures were measured with the NPs every other day at 5:00.



715 **Figure 4.** Vertical profiles of soil physical variables in pits dug in the polygon where our instrument station is located, during summers 2013 to 2015. (a) Temperature; (b) thermal conductivity; (c) volumetric liquid water content.



720 **Figure 5.** Seasonal evolution of the thermal conductivity, temperature and volume water content of the soil at 10 cm depth for the 2014-2015 season. The 5TM probes which measures both temperature and water content hourly is about 2 m from the TP08 NP, which measures thermal conductivity and temperature every 2 days.

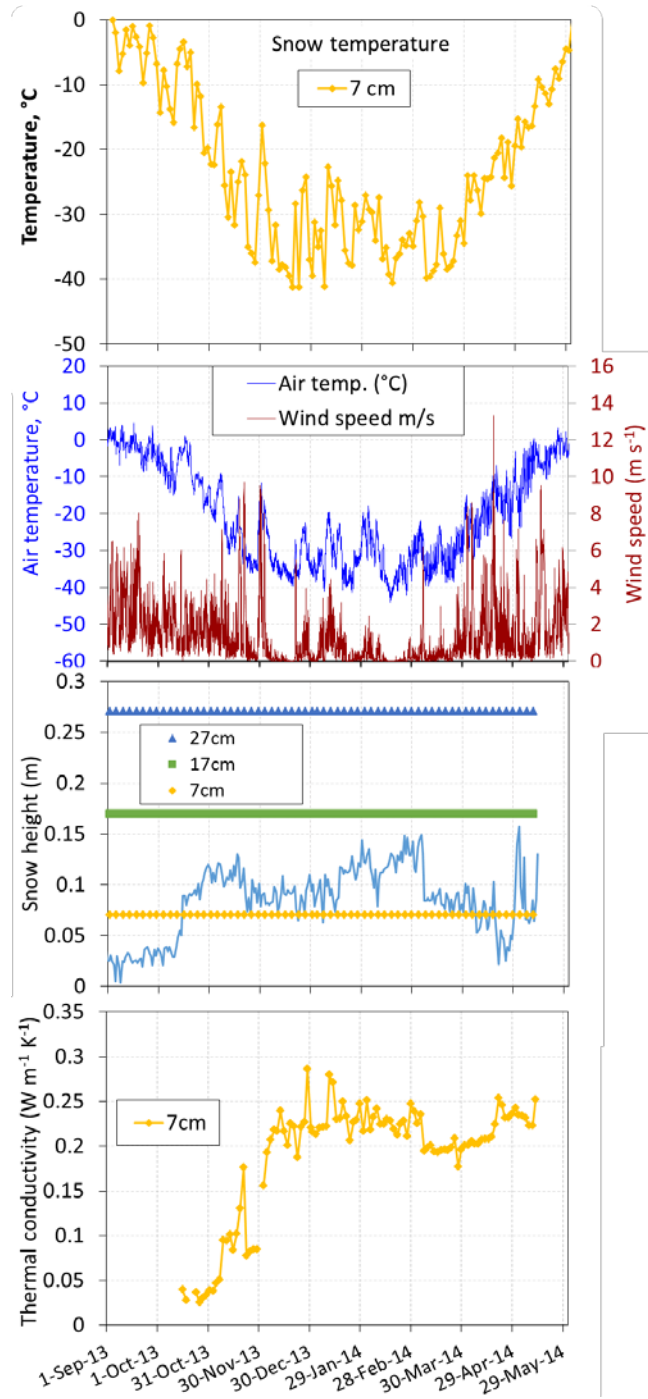


Figure 6. Snow temperature, air temperature, wind speed, snow height and snow thermal conductivity at 7 cm height during the 2013-2014 winter season at Bylot Island. The levels of the three thermal conductivity needle probes (NPs) are indicated in the snow height panel, showing that only the lowermost NP was covered.

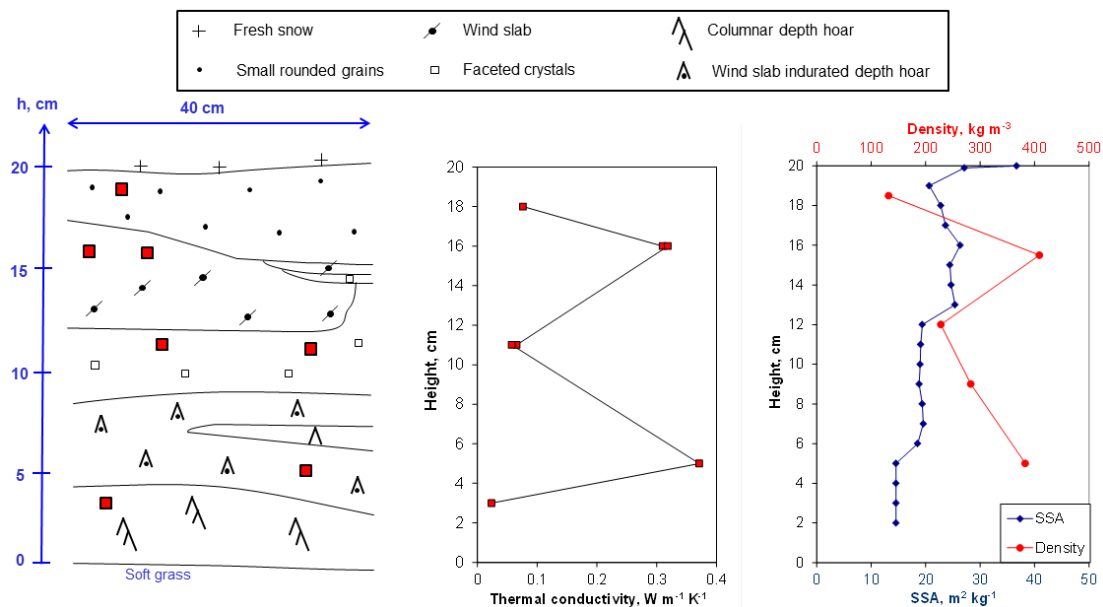


Figure 7. Stratigraphy and vertical profiles of snow physical properties near our study site on 14 May 2014. Fresh snow is just a 2 mm-thick sprinkling, also visible in the SSA profile. Density data are for the middle of the 3 cm-high sample. Snow type symbols are those of [Fierz *et al.*, 2009], except for the lower wind slab which transformed into depth hoar to form an indurated layer, as detailed in the text. Red-filled black squares in the stratigraphy indicate where thermal conductivity measurements were made.

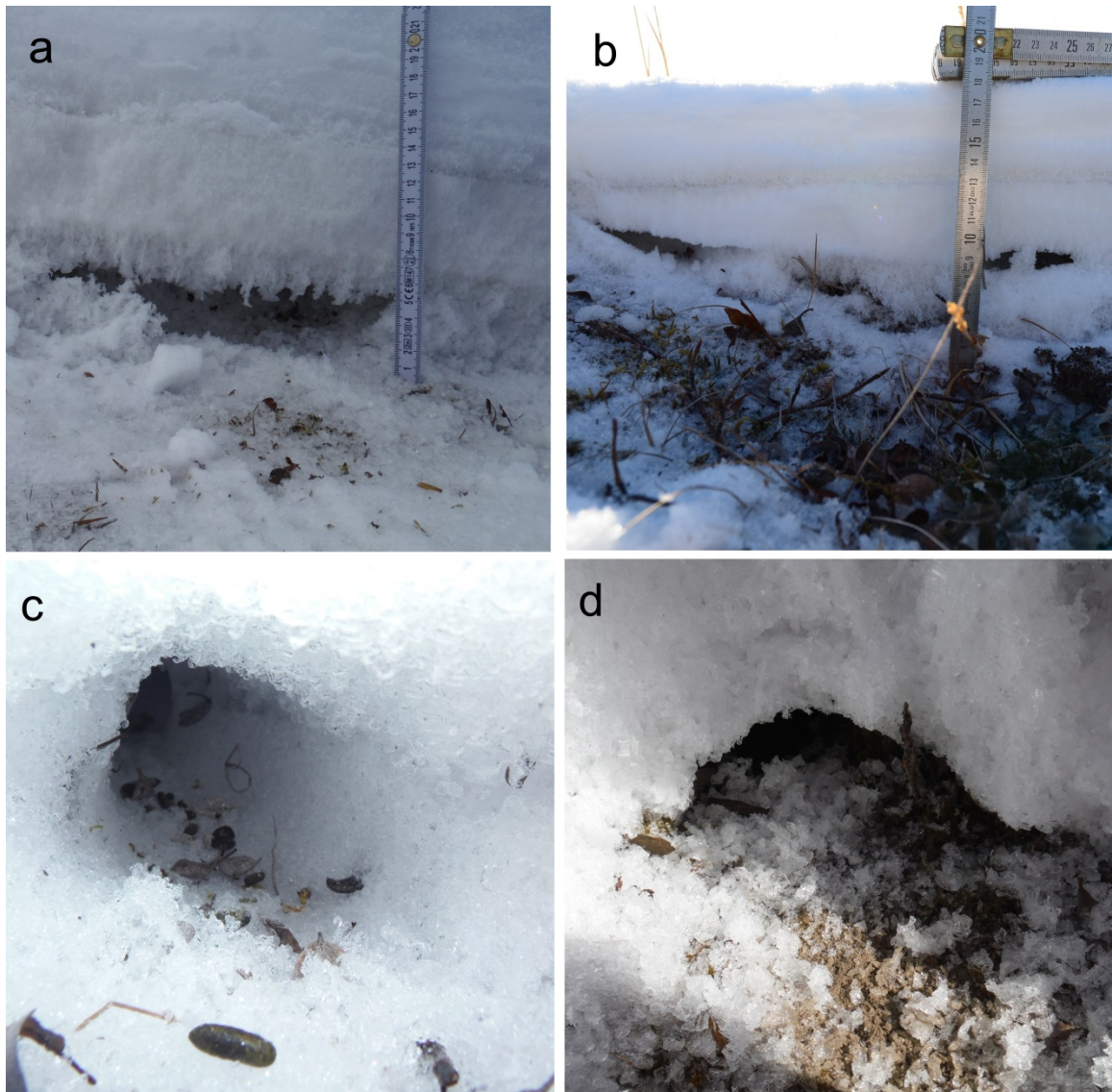


Figure 8. Gaps in the snow in the basal depth hoar layer. (a) and (b) gaps due to the spontaneous collapse of the depth hoar, following season-long mass loss because of the upward water vapor flux. (c) and (d) lemming burrows, easily identifiable by their regular shape and the presence of characteristic feces (c, foreground).

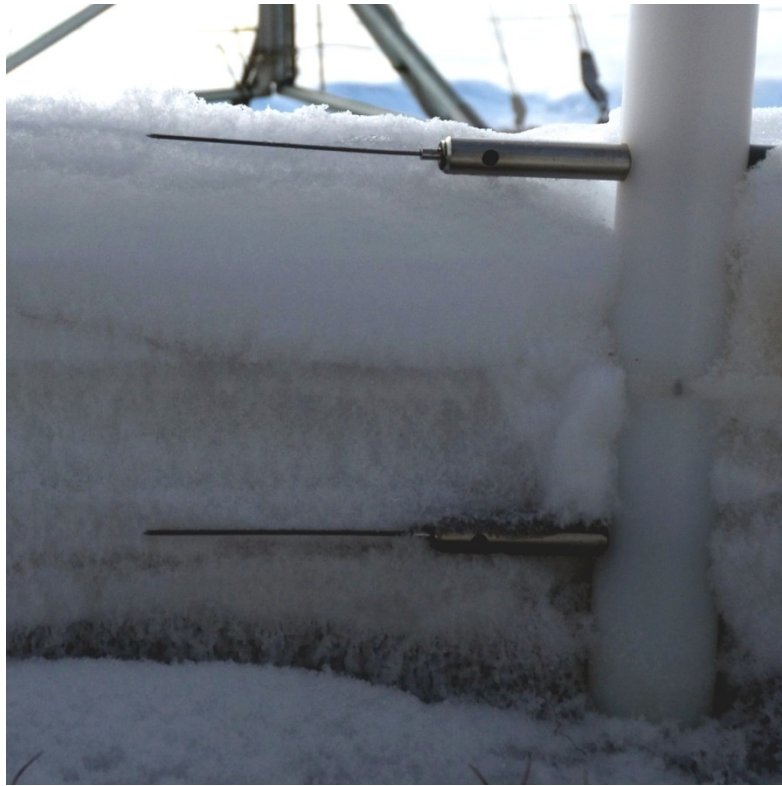


Figure 9. Photograph of the snow stratigraphy taken on 14 May 2014. The NPs are 7 and 17 cm above the ground. The various depth hoar and indurated depth hoar layers between 0 and about 11 cm are clearly visible, as well as the wind slab between 11 and 16 cm.

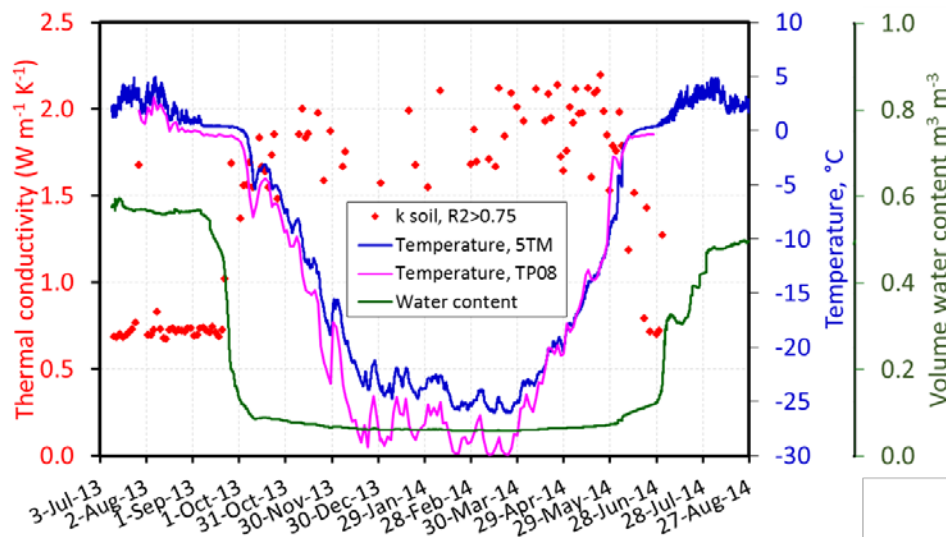


Figure 10. Seasonal evolution of the thermal conductivity, temperature and volume water content of the soil at 10 cm depth for the 2013-2014 season. The 5TM probes which measures both temperature and water content hourly is about 2 m from the TP08 NP, which measures thermal conductivity and temperature every 2 days.

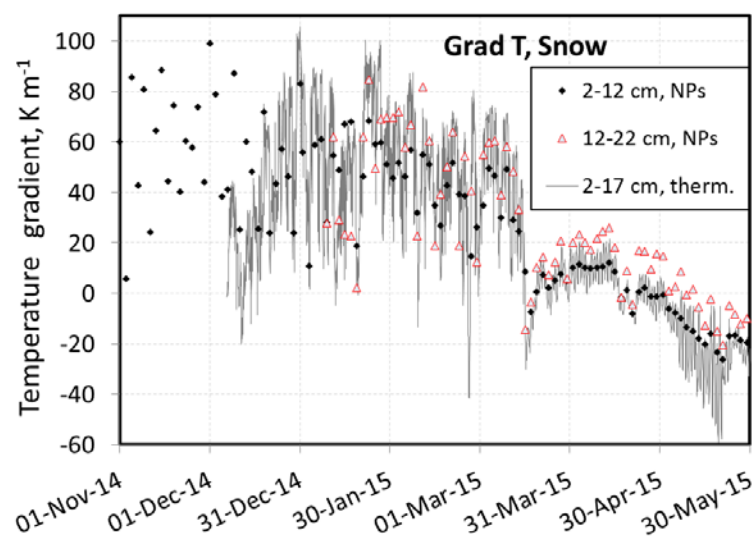


Figure 11. Time series of the temperature gradient in the snow. Values were obtained from the heated needle probes at 2, 12 and 22 cm, with a data point every 2 days. Thermistors at 2 and 17 cm also measured temperature every hour, and the values smoothed over 48 hours are shown with an hourly resolution. The different start dates of each curve are determined by the date where the snow height reached the relevant level.

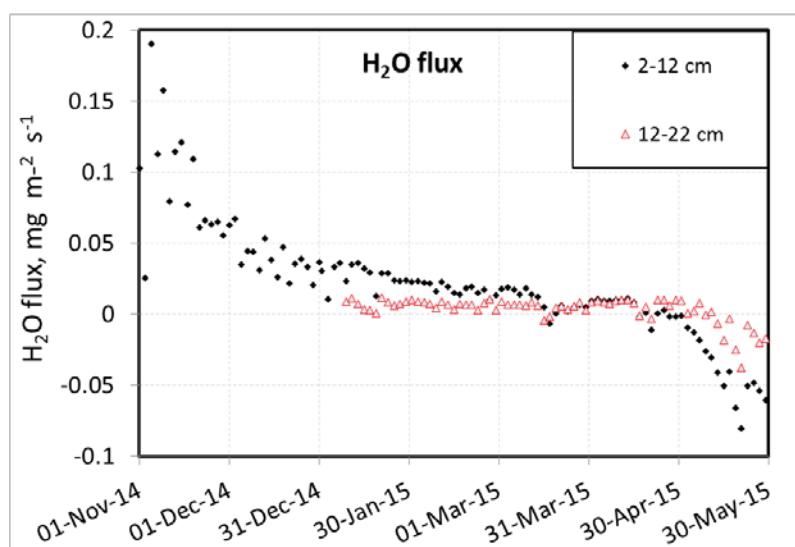


Figure 12. Time series of the water vapor pressure gradient flux at two levels in the snowpack. Positive fluxes are upward.

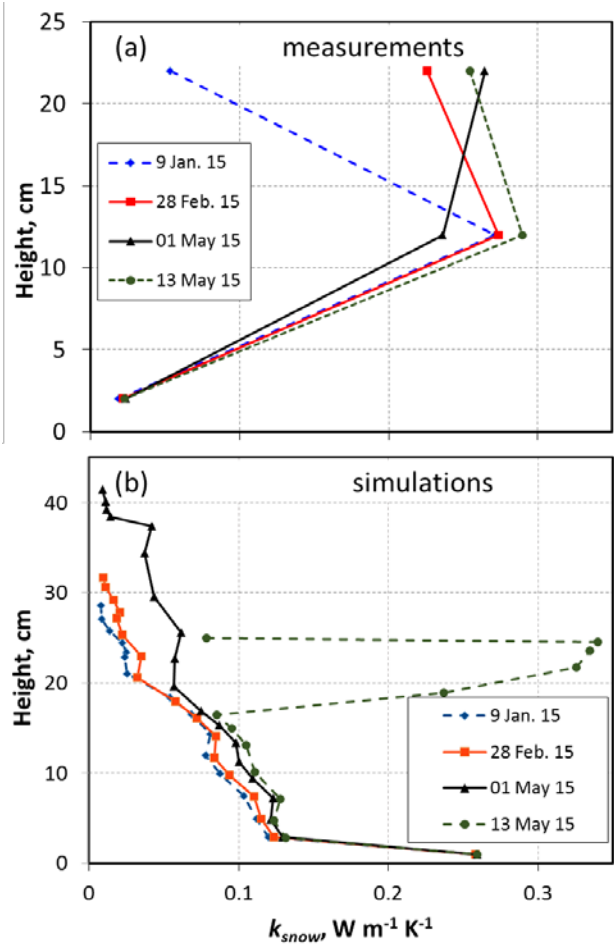


Figure 13. Vertical profiles of k_{snow} . (a) Measured by the needle probes; (b) modelled by CROCUS.