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Interactive comment on "Thermal conductivity of firn at Lomonosovfonna, Svalbard, derived from subsurface temperature measurements" *by* Sergey Marchenko et al.

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Journal: *The Cryosphere Discussions*
Manuscript: tc-2018-294: Thermal conductivity of firn at Lomonosovfonna, Svalbard, derived from subsurface temperature measurements
Authors: Sergey Marchenko, Gong Chen, Per Lötstedt, Veijo Pohjola, Rickard Pettersson, Ward van Pelt, and Carleen Reijmer

Reviewer: Ed Waddington

1 Overview

This paper is a thorough and commendable analysis of a set of shallow borehole temperature measurements from Lomonosovfonna, Svalbard, using a least-squares analysis to infer an effective relation between thermal conductivity and density while rigorously accounting for measurement errors in temperature, sensor depth, and firn density. Although the uncertainty analysis is relatively standard, the attention to detail is exceptional.

My major concern is that a"best" relation between conductivity and density may not exist. Although density is likely the most important control on conductivity, I expect that the microstructural texture of the firn is also very important. I would expect that the range of effective conductivities from the various studies (e.g. Figure 7) is due primarily to differing microstructural textures.

For example, firn with large grain-to-grain bonds should conduct heat significanltly better than firn of the same density with less-well-developed bonds. Although this study restricted modeling to periods with no melting of ice or freezing of water, nonetheless the presence of transient meltwater at other times has probably modified the microstructures in significant ways. The Lomonosovfonna conductivity is greater than in Sturm et al. (1997), and in Calonne et al. (2011) at all densities, perhaps due to greater amounts of melting?

Measuring microstructures with micro-CT scans is time consuming and expensive, and is not common (yet), but it may be needed to further advance the conductivity relations. In the meantime, any additional field data (e.g. by hand lens or other tools) on bond size, and grain size or elongation, might provide the next helpful step.

I am not saying this is a fatal flaw for the current paper, only that this point might merit more discussion in the manuscript.

In my view, the paper will be suitable for publication in *The Cryosphere* after revisions.

1.1 Scientific points

- Have you considered solving for themal diffusivity, as colleagues at Dartmouth have done, rather than for conductivity? Since k and ρ are both included in diffusivity, there is only one parameter to find. Does that decrease the scatter in the solutions? In the analysis in the manuscript, ρ seems to show up more as a complication than as a valuable result, and there is no comparison of inferred density against a transient densification model.

  Or is it more important to try to resolve both k and ρ?

- The manuscript focuses primarily on comparisons with two other models, i.e. Sturm et al. (1997), and Calonne et al. (2011). However, there are other models in the literature. Below is a brain dump of references relating to conductivity - some of these are already cited, and some are not. Could plotting up predictions from all these other models give readers a better sense of the spread among the current models, and therefore the importance of overlooked physical properties such as microstructure? Perhaps not adding clutter to Figure 7, but making an additional figure?

  Anderson EA (1976) A point energy and mass balance model of a snow cover. (doi:10.1016/S0074-6142(99)80039-4)

  Brandt RE and Warren SG (1997) Temperature measurements and heat transfer in near-surface snow at the South Pole. J. Glaciol. 43(144), 339–351

  Thermal properties and temperature distribution of snow/firn on the Law Dome ice cap, Antarctica. Antarct. Res. 2(2), 38–46

  Lüthi MP and Funk M (2001) Modelling heat flow in a cold, high-altitude glacier: Interpretation of measurements from Colle Gnifetti, Swiss Alps. J. Glaciol. 47(157), 314–324 (doi:10.3189/172756501781832223)

  Riche F and Schneebeli M (2013) Thermal conductivity of snow measured by three independent methods and anisotropy considerations. Cryosphere 7(1), 217–227 (doi:10.5194/tc-7-217-2013)

  Schwander J, Sowers T, Barnola J-M, Blunier T, Fuchs A and Malaizé B (1997) Age scale of the air in the summit ice: Implication for glacial-interglacial temperature change. J. Geophys. Res. Atmos. 102(D16), 19483–19493 (doi:10.1029/97JD01309)

  Schwerdtfeger P (1963) Theoretical derivation of the thermal conductivity and diffusivity of snow. IAHS Publ 61, 75–81 http://iahs.info/uploads/dms/061007.pdf

  Sturm M, Holmgren J, König M and Morris K (1997) The thermal conductivity of seasonal snow. J. Glaciol. 43(143), 26–41 (doi:10.1017/S0022143000002781)

  Van Dusen MS (1929) Thermal conductivity of non-metallic solids. International critical tables of numerical data, physics, chemistry and technology. McGraw-Hill New York, 216–217

  Yen Y-C (1981) Review of Thermal Properties of Snow, Ice, and Sea Ice. CRREL Rep. 81-10, 1–27 http://acwc.sdp.sirsi.net/client/search/asset/1005644

- Page 6, Equation (5) -
  Equation (5) uses the arithmetic mean of conductivity k at the nodal midpoints. This should be adequate for the exercise here, but for cases where the conductivity gets very small or zero, it is preferable to use the geometric mean

$$\left(\frac{2k_i k_{i+1}}{k_i + k_{i+1}}\right) \tag{1}$$

which actually goes to zero to prevent heat transfer across the interface when one of the bounding conductivites is zero, and prevents heat leakage to a node with very low conductivity. e.g. see page 44 in Patankar (1980), or many other texts.

Patankar, S.V., 1980. *Numerical heat transfer and fluid flow*, Hemisphere.

- Page 7, Equation (6) and line 15 -
  The objective function has to be nondimensional, since you are mixing temperature values and density values. Therefore, the weighting term σ_{ρ_i} cannot be set to unity as stated - it must be set to some characteristic density factor.

- Page 11, Line 13 -
  Why is L assumed to be 1 meter?

- Figures 2 and 4. -
  The units on the horizontal axes look impossible. For example, how can Spring 2013 begin only 40 days after Spring 2012 ends, and only 99 days after 21 April, 2012?

1.2 Editorial points and clarity

- A table of variables would be helpful for readers.

- *Data* are always plural. The word is often used incorrectly with a singular verb in the text.

- The units of conductivity are usually expressed as W m$^{-1}K^{-1}$. Is there a reason for separating the Watts into Joules per second?

However you decide to do it, at least be consistent. For example, Page 13, line 127 - $J(Kms)^{-1}$ *vs* Page 12, line 24, $J(smK)^{-1}$

- Page 15, line 27 -
  Where does the K^{-3} come from?

- Page 1, Line 13:
  As a basic physical property of a medium temperature of snow, firn and ice controls multiple processes occurring therein and at the glacier surface.
  I do not understand what this sentence is trying to say. Perhaps some commas could help?

- Page 2, Line 5:
  Since most temperature fluctuations occur at the surface, the dominant direction of heat flux is vertical:
  If temperature fluctuations are due to weather and climate, of course they are maximum at the surface, (particularly when latent-heat effects are negligible), but they actually occur at all depths. What message is this sentence trying to convey?

- Page 12, Line 11 -
  Spell *pattern*

- Page 2, line 4 -
  Cuffey and Paterson is a big book. It helps readers when you include a page number.
  Page 5, line 9 - Same comment.
  Page 6, line 6 - Same comment.
  Page 16, line 14 - Same comment.

- The abbreviation *ca* is used frequently for the latin *circa*, or "approximately". If the authors do not want to say *approximately*, then the appropriate abbreviation is *c*.

- Page 3, Line 20:
  The accumulation and melt rates estimated respectively from repeated radar surveys (Pälli et al., 2002; Van Pelt et al., 2014) and modeled surface energy and mass fluxes (Van Pelt et al., 2012) are 0.58–0.75 and 0.34 m w.e.year$^{?1}$*, respectively.*
  The subject of this sentence is very complicated, such that readers may not recognize it as a complete sentence on first reading. Can you re-write it in a simpler way?

- Page 3, line 20:
  What scale (in meters) is intended by *local-scale variability*?

- Page 9, line 3 -
  Something went wrong with the meters units. $J(smK)^{-1}$?

- Page 15, line 26 -
  Writing kgm^{-1}, the gm can look like grams, causing some reader hesitation.

- Page 16, line 12 -
  Summit is a named location, so it should be capitalized.

- Figure 4 -
  It would help readers if you could add Spring, Fall, and Year labels, as on Figure 2.