Response to Referee Comments by Martin Lüthi

Thank you very much for your suggestions and comments. All comments by the reviewer are in bold with our responses below. Changes we will make to the text of the manuscript are italicized.

General Comments:

While the argumentation of the paper is logical and easy to follow, I have some reservations about the claims of measurement accuracy, especially given the very crude calibration in the field after deployment.

We appreciate you highlighting this concern and agree that more information should be added so readers can evaluate our results. We have added more information about the sensors used and our calibration methods below when addressing your specific comments. However, we do want to stress that the major results of this study are the observed temperature changes – which are based on sensor resolution. We are not as interested in the absolute temperature of the ice column, and potential calibration errors do not affect the strong cooling signal we observe throughout the lowest portion of the ice column.

The description of the "modeling" is quite unclear. First it sounds like no numerical model is used, but then suddenly there are model results. Please provide details on the model used (FE, FD, ...), spatial and temporal resolution, solution accuracy, implementation details (if not from a standard package). How does this model treat the phase transition (Stefan Problem)? Is there an enthalpy scheme involved (probably not, why not)? Is dissipation due to ice deformation considered as changing source? How is vertical stretching dealt with, which alters temperature gradients, and therefore heat fluxes, over time? Initial and boundary conditions for the modeling exercise seem rather ad-hoc. They should be justified, and it should be shown that the conclusions don't depend on the specifics of these values.

We understand the confusion over our observed temperature profile comparison to modeled temperature profile in using a 1-D finite difference diffusion model. Our intention with this was to simply highlight the fact that other heat sources must be altering the vertical temperature field (which is a rather obvious conclusion). However, we found it interesting that the areas within the observed profiles that were warmer than the idealized diffusion profile are often where we observe cooling. This result suggests to us that previous heating occurred to warm ice, and ice is now cooling back to a more diffusive state.

However, given your concerns about the modeling methodology, we have re-written this section. Rather than introduce a section describing modeling methodology, we have decided to remove these comparisons from our analysis. Instead, we compare each collected temperature profile to the site-average temperature profile. The average temperature profile should be shaped by all processes that transport heat within the ice column as it moves from the ice divide to our field site in the ablation zone (dissipation, geothermal heat fluxes, vertical stretching, latent heat sources, etc.). Deviations from this mean profile will highlight regions that reflect recent changes to heat sources or sinks. Therefore, we have rewritten the two paragraphs from line 126 – 145 as follows:

In addition, we also highlight regions of the static profiles that are not only warming or cooling anomalously, but that may be warmer or cooler than would be expected given the average vertical temperature field at our site. The shape of the site-averaged temperature profile results from ice integrating changes in boundary conditions and all upstream thermomechanical processes. Any deviations from this averaged profile within each collected temperature profile will highlight thermal regions that reflect changes to either the local boundary conditions or heat sources or sinks. These changes must have occurred recently for the closely spaced boreholes to capture temperature fields that do not match the average vertical temperature field at the site.

Discrepancies between each collected profile and the site-average temperature profile are shown in Fig. 5. Generally, there are positive deviations within the lowest portion of the ice column where there is a clear signal of cooling in boreholes 14SA, 14SB, 14N, 15CA, and 15CB, showing where temperatures in these boreholes are higher than those in the site-average profile. Encouragingly for this analysis, temperatures in the upper half of the 14N and 15CA profiles are warmer than the site-average profile and cooling occurs over time. While the pattern of temporal temperature change in boreholes 15S and 15E are not as clear, 15E is colder throughout the full-ice depth than the mean profile, but this borehole also is where sensors record the most warming throughout the profile. Spatially, the southeast portion of our field site does not have a cooling signature in relatively warm ice near the bed, which is evident throughout the other boreholes that have time-series of temperature measurements.

The conclusion that refreezing of water-filled crevasses is intriguing, but it is unique? Could vertical stretching/compression, and thus altered heat fluxes, account for the observed cooling?

We have suggested within the manuscript that likely the solution to this problem is not unique, because we do not know the configuration of the basal stress state at our site that could introduce/remove sources of strain and dissipated heat. However, given the surface strain observed we do not believe that vertical compression would alter heat fluxes sufficiently to cause the cooling we have observed. Given that we are looking for a likely discrete heat source that manifests in cooling, we believe that basal crevasses are the most likely mechanism to do this.

<u>Specific comments:</u>

Line 36: Most other studies also have time series often at higher time resolution (minutes).

We have changed the sentence to read as follows:

"Our data provide sub-daily continuous records of ice temperature over a 2-3 year period, longer than many similar temperature time-series datasets."

Line 57: Please provide information on the manufacturer/series, and on the type of AD converter (with the manufactured probe, or externally on an NTC or PT100)

Thank you for pointing this out. The sentence now reads as follows:

"Cat-5 cables instrumented with TMP102 temperature sensors that have 12 bit analog-to-digital converters were installed in the boreholes after drilling and logged with a custom data logger at the surface. Each temperature sensor was controlled by a separate downhole microprocessor that ensured that the sensor was powered only as minimally required to obtain a reading. The paired microprocessor handled all digital communications, power control and data processing to minimize errors caused by sensor self-heating."

Line 61: Yes, it will stabilize at the phase change temperature, but what is this freezing point? It depends on all kinds of things, dissolved air, soluble and solid impurities, crystal curvature, etc. If so, you can only give temperature with respect to local phase change temperature (which itself is not static, but depends on the ambient pressure, which as you claim in your paper changes due to connection to basal water (among other things)). On Gornergletscher, the temperature variations due to variations in the subglacial system were 0.5 K. So, you don't really know what the exact temperature is."

We will incorporate which CC gradient was used for the freezing point calibration. And your point is well-taken; both due to the uncertainty in the freezing point itself and changes in ambient pressure, we will reduce our confidence level to 0.5 °C. This will affect our confidence in the static profiles, but will not influence the calculated temporal rates of temperature change which relies on the sensor resolution. This section now reads:

"We perform a freezing-point calibration, using a Clausius – Clapeyron gradient of -7×10^{-8} °C Pa^{-1} (Cuffey and Paterson, 2010). However, due to the uncertainty in the Clausius – Clapeyron slope given dissolved air and impurities within the ice and the ambient pressure at the time of calibration, we are confident in the sensors' absolute accuracy to approximately 0.5 °C."

Line 62: You mean "absolute accuracy"? I don't think so, this depends a lot on the CC-Gradient which you don't know.

See correction above.

Line 59: No lab calibration?

Line 65: How much electrical power was dissipated in the sensors? Was the measuring interval ever changed? These are important sources of heat (we spent days puzzling over sudden cooling in boreholes, until we figured out that dissipated electrical power was to blame (Ryser, 2013).

In response to these two comments above, the measurement collection times never changed, thus the measuring interval was constant. Great care was taken to ensure that measurements were taken under exactly the same electrical state over the 2-3 year time period for the reasons that you discuss above. Although we did not do laboratory calibrations on the individual sensors used, extensive laboratory testing was done on representative sensor strings in a cold room to ensure that the sensors had a stable resolution and that problems associated with self-heating could be avoided.

Line 70: It seems that analyzing exactly this transient temperature field would provide convincing evidence that another heat source is needed.

Thank you for this suggestion. We believe that we have shown the need for a heat source to manifests in cooling by allowing the sensors to equilibrate with the ambient ice temperature and discussing a number of thought experiments to eliminate potential processes that might result in cooling.

Line 71: What does "electrically isolated" mean?

Changed to read: *"in the environment isolated from electrical noise"*

Line 74: Please specify whether these jumps happen in near-temperate conditions (i.e. closer than 0.5 K from the pressure melting point). If so, these jumps (at only 4-hour intervals) could be due to subglacial pressure changes. It would be useful to also check these and show time series of temperature and pressure (at least in Supp. Material). If the temperatures are much below the melting point, then this is very likely sensor/electronics noise.

The jumps are due to the nature of the low power, long cable, and data transfer protocol that was developed in house for these instrument strings. The protocol is not as fully robust as a full i2c protocol and has the potential for very occasional line conflicts lasting less than one bit count, The protocol has many advantages in terms of power saving and computational expense, reducing down-hole self-heating. The occasional glitch was a known and accepted problem. If the reviewer is interested; the protocol is a modified and simplified i2c protocol, using modified RS-485 electrical cable protocol. It is the simplified buss assertion part of the protocol that leads to the occasional one bit glitch.

Line 81: A short description of the heat flow model is missing, and here would be a good place to do that. Just method, resolution, BCs etc.

Because we have eliminated our comparison to best-fit modeled diffusion profiles, we will not discuss any modeling here. Our modeled crevasse field in the discussion is just simply to illustrate how distributed cooling could occur, we will leave our discussion of this modeling in the supplement.

Line 84: Give temperature values.

We have added: *"Temperatures are lowest in approximately the middle of the ice column, ranging from ~ -12 °C to -10 °C and increase to ~ -11 °C to -4.5 °C at the surface. Temperatures also increase towards the bed, reaching temperatures that range from approximately -0.9 °C to -0.5 °C."*

Line 86: This is not visible in Fig. 2. Show a close-up of the area close to the bottom, the lowest 10 or 50 m or so maybe as an inset. Also indicate the CC gradient there. Since this is the main topic of the paper, basal temperatures should be shown in detail.

Thank you for this suggestion. We have updated Fig. 2 to include an inset of the lowest 20 m of the ice column. We have also plotted the CC-gradient using the two end member values given in Cuffey and Paterson (2010).

Line 94: It would be interesting to show something like a longitudinal or cross profile of near-basal temperatures. Does this produce anything systematic?

We believe that this can be seen in Figure 5, with 15S and 15E showing no clear cooling signature. We have added this sentence at the end of the paragraph that we added above:

"Spatially, the southeast portion of our field site does not have a cooling signature in relatively warm ice near the bed, which is evident throughout the other boreholes that have time-series of temperature measurements."

Line 110: Conventionally, *k* is used for conductivity and kappa for diffusivity. It would help to use these standard symbols here (first I thought the equation was wrong).

We have made the changes throughout the document to use kappa (κ) when referring to thermal diffusivity of ice.

Line 111: Please give the values used for these calculations, including references. Especially kappa is important here.

We have added a table in the supplement with the values used in this study.

Table S1. *Constants used in this study (Cuffey and Paterson, 2010)*

Property	***Variable***	***Value***	***Units***
Density of ice	ρ_i	*917*	*kg m^{-3}*
Density of water	ρ_w	*1000*	*Kg m^{-3}*
Heat capacity of ice	C	*2097*	*J kg^{-1} K^{-1}*
Latent heat of fusion	L_f	*3.335 x 10^{5}*	*J kg^{-1}*
Thermal conductivity of ice	K	*2.1*	*W m^{-1} K^{-1}*
Thermal diffusivity of ice	κ	*1.09 x 10^{-6}*	*m^{2} s^{-1}*
Clausius-Clapeyron slope	γ	*-7.4 x 10^{-8}*	*°C Pa^{-1}*

Line 118: This is just an analytical equation, so I would not call this a "model".

This sentence has been changed to:

"Comparison of our data and expected temperature changes from the analytical equation (Eq. 1), indicates that the curvatures in our temperature profiles cannot produce the observed temporal changes of temperature over time through diffusive vertical heat flow alone."

Line 120: Calculated. You just take measured d^2T/dz^2 values.

Changed modeled to calculated.

Line 148: The question is rather: are heat sinks necessary? Maybe this simple model is insufficient, and warming is simple. If heat sinks are necessary (as you argue from your 1-D analysis of heat fluxes), what temperature gradients would be needed horizontally to account for the mismatch?

From our 1-D analysis, we could convert these missing heat fluxes into necessary temperature gradients. Because all negative heat fluxes are required in all boreholes across the site, this indicates that heat must be flowing out of the instrumented block of ice, which we later discuss in line 275.

Section 4.2 – 4.2.1 has been changed to:

"Pervasive cooling in the lowest portion of boreholes where ice is warmer than the site-average profile in some, but not all, of our borehole data is enigmatic, since multiple heat sources exist near the bed, but identifying heat sinks is problematic. In addition, the non-uniform nature of cooling near the bed requires explanation. We dismiss several possible heat sinks below."

Additionally we have updated the sentence on line 275 to read:

"Given negative heat fluxes are required in the lowest portions of all boreholes (Fig. 4) to create observed cooling, thermal energy likely diffuses away from our site in 3-dimensions, which would result in cooling not captured in our vertical 1-D modeling."

Line 153: How? How would heat be transported to the melting front?

The sentence now reads:

"Some melting can occur in this temperate ice as the pressure field varies due to ice flow, and transient increases in pressure can decrease the melting point."

Line 161: Yes, and you could actually quantify this (as was done i.e. in Lüthi et al., 2002). For this, the data close to the CTS should be enlarged.

Because this has the opposite effect of the observed cooling, we make no attempt to quantify this; however, we have noted that Lüthi et al. (2002) has performed this quantification.

"Any interstitial water present in the ice would then be colder than the new melting temperature and would then refreeze. Lüthi et al. (2002) estimated the water content of the temperate layer of ice near the bed of Jakobshavn Isbrae has a moisture content of ~ 1%. However, refreezing releases latent heat into the surrounding ice, resulting in warming rather than cooling…"

Line 191: Change "heat" to "dissipated heat".

We have made this change. It now reads *"... accumulates dissipated heat near the bed where strain rates are highest."*

Line 193: I would qualify this better. This internal strain heat source is removed while frictional heating prevails at the base.

The sentence now reads:

"At our site ice moves primarily by basal sliding (Maier et al., 2019), and this internal strain heat source is removed although frictional heating still exists at the base."

Lines 194-195: Yes, but does it matter why the profile looks as it does? If you measure cooling, but the profile does not provide enough thermal gradient, then you either need more dimensions for diffusion or an active cooler.

Yes, and we have shown that the shape of our temperature profiles that would result from accumulating strain heat will not produce cooling from vertical conduction alone. We have added a sentence to explain this at the end of the paragraph.

"Additionally, we have shown that that the shape of the temperature profiles that would result from previously accumulated strain heat near the base will not produce the magnitude of observed cooling from vertical thermal conduction alone. An additional heat sink must be required."

Line 203: Cooling caused by variations in the basal boundary stress state is not obvious, please explain.

The sentence now reads:

"However, it does point out that variations in the basal boundary stress state can cause minor heating, or cooling if strain and thus strain heating is removed or reduced."

Line 221: By definition of "crevasse", probably yes. But I doubt that basal cracks are as nicely aligned as surface cracks. Deep in crevasses the patterns become chaotic, and this is probably even more so if they form under water. So maybe this is just some void space that was water filled for a while and refreezes. The exact shape probably does not matter for the discussion at hand, but this could be quite spongy.

We agree that these are likely not simple planar features. Additionally, even if they form perpendicularly to the bed, deformational gradients will deform these features, and they potentially can intersect more recently formed crevasses. However, to simply model the heat source, we treat basal crevasses as planar features. We have changed this section to read:

"Basal crevasses can have a thermal influence on discrete, but large regions of ice. Because these fractures are distinct features, the fact we do not see a clear cooling signature in

relatively warm ice throughout the base of the ice column at our site is not surprising. Slight warming in cold ice in borehole 15E and no clear signal in borehole 15S provides evidence that the ice is being affected by a thermal process that is not distributed in nature.

Multiple fractures can open similar to crevasses at the surface, and their growth is likely vertically restricted above the bed due to the cold, stiff central core of the ice column which reduces fracture propagation. Therefore, these features only affect the lower portion of the ice column. Additionally, basal crevasses likely are not simple planar features, strong deformational gradients near the bed can alter their shape and cause them to intersect more recently formed crevasses. Although basal crevasses may not be more complex than an en échelon arrangement of vertical fractures, for simple modeling, we focus on the thermal disturbance created by basal crevasses that allow the influx of a plan of water from the bed up into the cold ice. Accurately modeling the thermal disturbance…"

Line 222: Why would basal crevasses be vertically restricted when propagating from the bed?

See rewritten section above.

Line 240: Again, better use kappa.

We now use κ throughout the manuscript for thermal diffusivity.

Line 251: This is somewhat ambiguous. Better: "for the time since water-filled basal crevasses were formed".

The sentence now reads: *"It is tempting to estimate the time since water-filled basal crevasses were formed."*

Line 263: They also could form under dry conditions given enough longitudinal or shearing stresses. This is just a fracture process. But they might not open up, unless water under high pressure forces them open and precludes rapid healing.

We are trying to highlight the subglacial conditions at our site are conducive to basal crevasse formation because of high basal water pressures observed in Greenland's ablation zone. The beginning of this paragraph has been modified as follows:

"Basal water pressures at or above ice overburden pressure promote the growth of basal crevasses 10s of meters above the bed."

Line 268: there are many observations of basal seismic sources compatible with fracturing.

Thank you for pointing this out. We have added:

"Additionally, observed stick-slip behavior and hydraulic jacking from rapid delivery of surface meltwater through passive seismic surveys could provide another mechanism for basal crevasse formation (Moore et al.,2013)."

Reference added:

"Moore, P. L., Winberry, J. P., Iverson, N. R., Christianson, K. A., Anandakrishnan, S., Jackson, M., Mathison, M. E. and Cohen, D.: Glacier slip and seismicity induced by surface melt, Geology, 41(12), 1247–1250, doi:10.1130/G34760.1, 2013."

Line 273: This is incorrect. There is no "abrupt warming" due to refreezing, but the boundary condition at the crevasse wall is melting temperature until all water is frozen. So the width of the crevasse simply determines how long it exists until completely refrozen.

We have changed the sentence to read:

"The 1-D temperature field evolution illustrates the warming that occurs due to the release of latent heat immediately as the crevasse completely refreezes."

Line 275: So do a 3D modeling, this is not hard and one standard example in any Finite Element code (e.g. MOOSE, Libmesh, MARC, Ansys, Comsol).

We appreciate the suggestion. However, like other recent observational studies of Greenland ice temperature (e.g. Seguinot et al., 2020, Doyle et al., 2018, Hills et al., 2017, Harrington et al., 2015) that do not attempt highly detailed modeling, we would prefer to keep this study focused on what the observations explicitly show. Particularly now that we have removed comparison to modeled profiles and only compare our temperature profiles to site average profiles, we believe that the results will come through stronger without spending too much of the text describing a 3-D modeling exercise and associated assumptions.

Line 279: Moulins are not linear features, but usually a series of vertical shafts connected through meandering passages, much like any Karst cave system. And potentially they continue as intraglacial channels of arbitrary direction at depth (as e.g. observed by Catania).

We agree that moulins are likely not nice linear features; however, we model them as such since they appear much more pipe-like at the surface. We have added language to indicate that these may be complex features.

"While the internal architecture of moulins is likely complex, as a simple model, we conceptualize moulins as linear pipes that release thermal energy from the surface to the bed because of how these features are manifested at the surface."

Line 282: Moulins usually form in a row with certain spacing, since surface features leading to crevasse formation are stagnant while the ice flows through them (Catania, 2010). But I agree that moulins are probably not the best explanation for the features unless they themselves are some kind of crevasse system at depth. Nobody knows.

Lines 283 – 284: As mentioned above, active moulins are not important for the argument, but active moulins times velocity which gives their spacing along the flow line. Since they

get advected and re-created every 100 m (or so), quite a large portion of the ice could be affected by their thermal influence, but extremely inhomogeneously.

To address these two comments above we have added:

"In the ablation zone surrounding Issunguata Sermia, active moulins have a mean density of 0.1 per square kilometer (Smith et al., 2015), and Catania and Neumann (2010) found relict moulins to be spaced ~ 1 km apart, which suggests that it is unlikely that multiple moulins have thermally altered the instrumented block of ice with a surface area of ~ 0.125 km^2."

Added reference:

Catania, G. A. and Neumann, T. A.: Persistent englacial drainage features in the Greenland Ice Sheet, Geophysical Research Letters, 37(2), doi:10.1029/2009GL041108, 2010.

Line 294: But: at your site there is no temperate layer to support this. And at our sites (and at Store) the temperate ice is mostly stiffer than Paterson would make us believe. This story is much more complicated.

This section reads:

"The lack of a thick basal temperate ice layer indicates the transient thermal influence of basal crevasses. Ice viscosity is highly temperature dependent, thus basal crevasses could create regions of temporarily enhanced deformation, although previous observations in Greenland have shown that deformation rates in temperate ice are often lower than theory predicts (e.g. Ryser et al., 2014; Doyle et al., 2018; Maier et al., 2019)."

Added reference:

Ryser, C., Lüthi, M. P., Andrews, L. C., Hoffman, M. J., Catania, G. A., Hawley, R. L., Neumann, T. A. and Kristensen, S. S.: Sustained high basal motion of the Greenland ice sheet revealed by borehole deformation, Journal of Glaciology, 60(222), 647–660, doi:10.3189/2014JoG13J196, 2014.

Line 302: Exactly. So these are probably not just nice cracks as we observe at the surface, but a chasm of destroyed ice intermingled with water, much like the underside of icebergs. Or like the Jakobshavn surface filled with water. So maybe a sponge-like structure, or a chaotic network of cracks in all directions is a good mental picture. "Crevasse" somehow alludes to en echelon, nicely shaped cracks.

We agree that the basal hydrologic system is likely complex. However, we feel that these two observations point out the intricacies of the hydrologic system without further speculating on its characteristics.

Line 328: DOIs should be given for all references.

We have added DOIs to references where they are missing if a DOI is available.

Technical corrections:

Line 12: Change strain heat to strain heating

We will leave this as strain heat to maintain the parallelism in the sentence.

Line 17: Change temporal to transient

Changed.

Lines 28 – 32: Change references Lüthi et al. to Lüthi et al.

We have changed this throughout the document and apologize for the typographic error.

Lines 28 – 33: Probably could make these citations less repetitive, now they are repeated after each sentence.

We will include them all at the end of this last sentence as a list *(e.g. list of references)*.

General technical comment - references to figures should be spelled out (e.g. Figure 2 instead of Fig. 2) and equations should be spelled out (e.g. Equation 2).

We are following the instructions listed under The Cryosphere Manuscript Composition that say:

> “The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that...".”

Additionally these instructions say:

> “In the text, equations should be referred to by the abbreviation "Eq." and the respective number in parentheses, e.g. "Eq. (14)". However, when the reference comes at the beginning of a sentence, the unabbreviated word "Equation" should be used, e.g.: "Equation (14) is very important for the results; however, Eq. (15) makes it clear that...".”

Line 109: Remove parenthesis around the Q term in Eq. (1)

We have removed these parentheses.

Line 123: Remove “temporal”.

We have removed this word.

Line 149: Change dismiss to discuss?

Changed.

Line 251: A timescale?

This sentence has been changed to read:

"It is tempting to estimate the time since water-filled basal crevasses were formed."

Line 252: Change under constrained to under-constrained.

Changed.

Line 257: Change decay to dissipation.

Changed.

Line 291: Change strain heat to strain heating.

Again, we will leave this as is for sentence parallelism.

Line 315: Is "warm" a verb? If so, maybe it should be "warms".

This can serve as a verb, and because we are talking about basal crevasses, which is plural, we will use the plural form of the verb, warm.

Figure comments:

Figure 1: Black triangles are barely visible. Why not use more colors, also for the labels? Source and year for the WorldView 2 Image?

We have made the WorldView 2 image lighter, and increased the symbols used to indicate borehole and GPS station locations. Additionally, we have increased the font size to make the figure more readable:

Updated figure and caption:

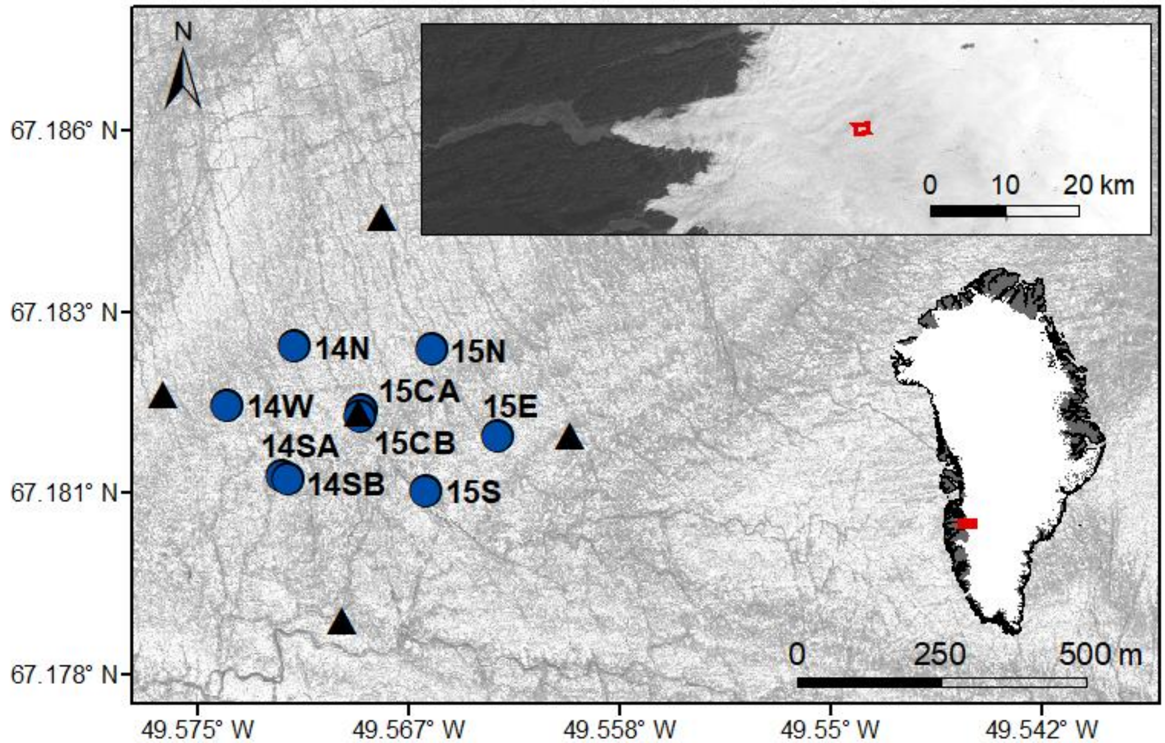

Figure 1: Map of the field location showing the layout of the 9 boreholes (blue dots) and the 5 GPS stations (black triangles). Borehole nomenclature is determined by the year that they were drilled and the direction from the center borehole and GPS station. The boreholes are located ~33 km from the margin of Issunguata Sermia outlet glacier shown in a LANDSAT 8 image taken in July 2014 in the upper-right inset. The location in southwestern Greenland is shown in the lower inset and boreholes are plotted on a WoldView-2 image from July 2012 (Copyright 2011, DigitalGlobe, Inc.).

Figure 2: Wouldn't distance below surface be more meaningful for the full plots? Then you could also plot the Clausius-Clapeyron gradient which is very important, especially for this study. Maybe just have an inset with the bottom 50 m or so and the CC-Gradient? The gray legend is not easy to read, just change it to white background.

We appreciate these suggestions and have added the CC-gradients and an inset showing the lowest-most temperatures. We will continue to plot ice temperatures with respect to height above the bed because we believe this reference frame makes the most sense as we discuss temperatures in the lowest portion of the ice column.

Updated figure and caption:

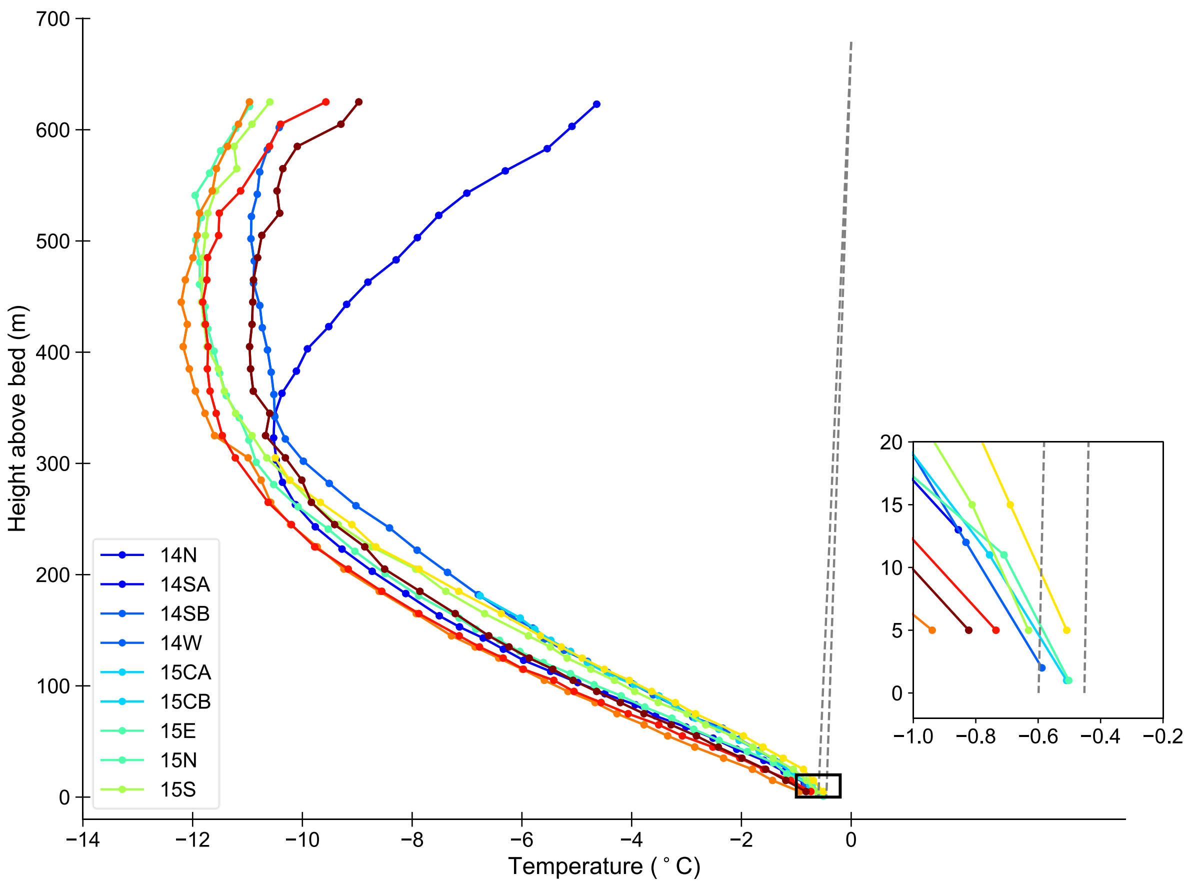

Fig 2: Temperature profiles for each borehole plotted with respect to each sensor's height above the bed. Sensor locations are marked with points and temperatures between sensors are linearly interpolated. Dashed lines indicate the range of pressure melting temperatures given the various Clausius-Clapeyron gradients presented in Cuffey and Paterson (2010). Black box indicates the extent of the inset showing temperatures in the lowest 20 m.

Figure 3: Use colored dots, and larger fonts. Also, the depths don't have to be repeated in each subplot. It might also be useful to show the temperature profile in each panel with a distinct color, but maybe this is just too confusing. Or at least indicate CTS and height above bed of the temperature minimum in each panel.

While we do understand and appreciate your suggestion to use color for the following plots, we feel that it would actually make it less accessible to more readers. Additionally, because the CTS height is essentially the same as the bottom-most sensor of each profile, we do not think it would add much detail to this plot. We have enlarged the font size in this figure and reduced the axis redundancies to increase readability.

Updated figure and caption:

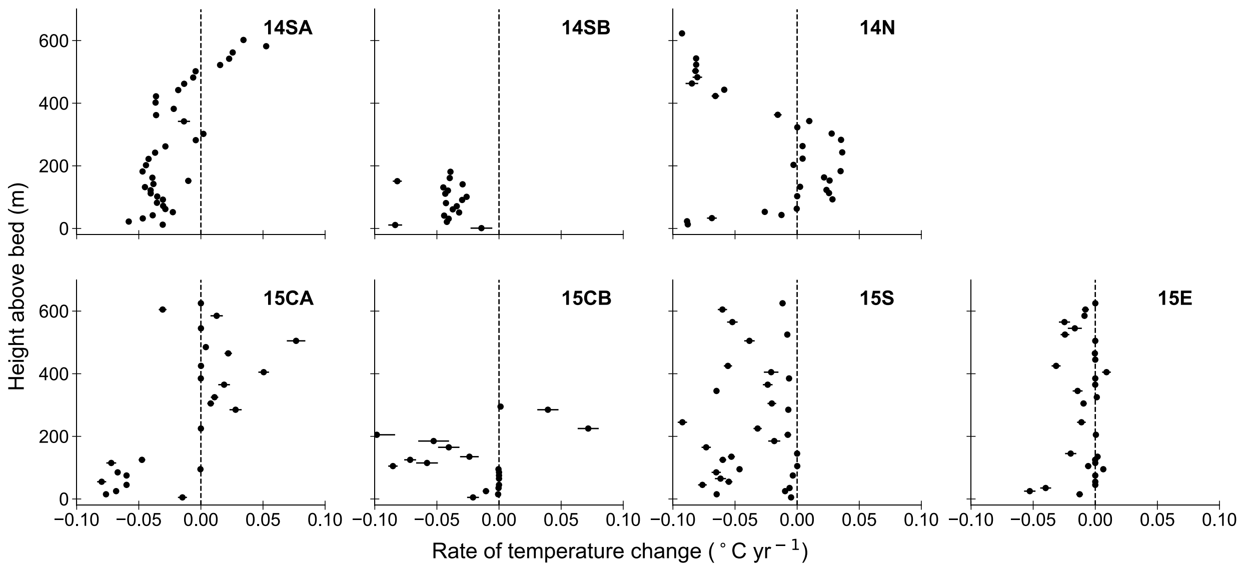

Figure 3: Rates of temperature changes for each borehole plotted against each sensor's height above the bed. Error bars indicate 2 standard errors from the mean rate, determined by the linear regression.

Figure 4: Use colors for the curves. Also change units to mW m^{-2}. Why are there less panels than in Figure 3? Could they be combined, as they show almost the same?

Thank you for suggesting changing the magnitude of the x-axis. We have made this change. Additionally, we have added the missing non-full-depth profiles that were missing. While this plot is very similar to Fig. 3, this plot is part of our analysis, and we do not want readers to get confused by displaying results and analysis in the same plot. We will leave it as a separate figure.

Updated figure and caption:

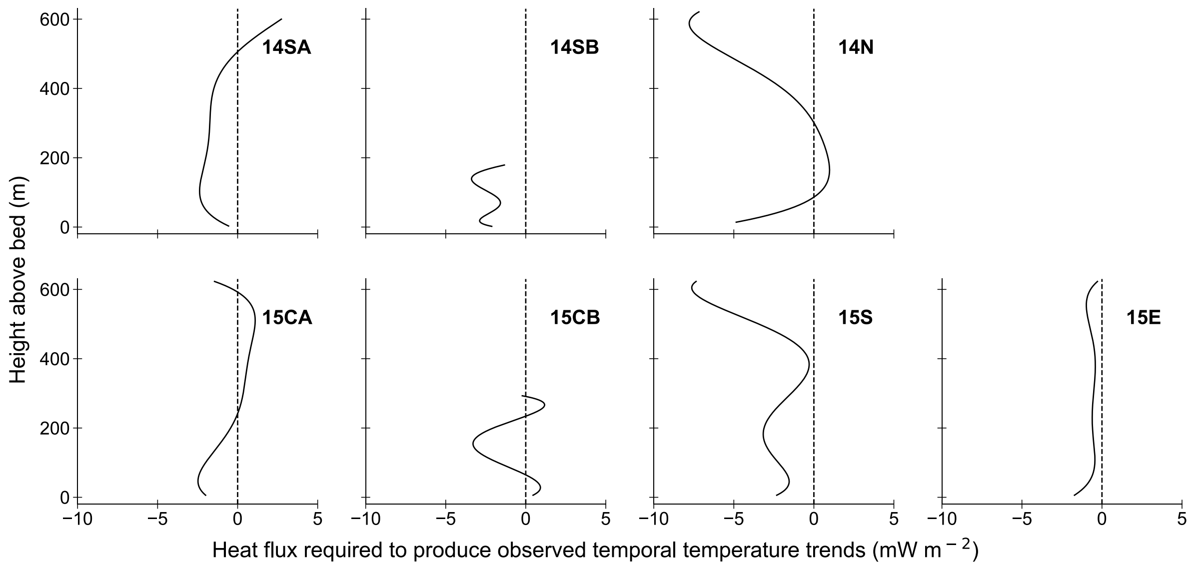

Figure 4: Additional heat fluxes required to maintain observed rates of temperature change if the collected static temperature profiles evolve through vertical conduction over time. Dashed line indicates the switch between a required heat source or sink.

Figure 5: Colors might be more useful, same as in Fig. 3. Why only show full-depth profile, other profiles would be as interesting.

We have added the other profiles to this figure, which now examines temporal temperature trends plotted concurrently with observed temperature profile deviations from the site-average temperature profile.

Updated figure and caption:

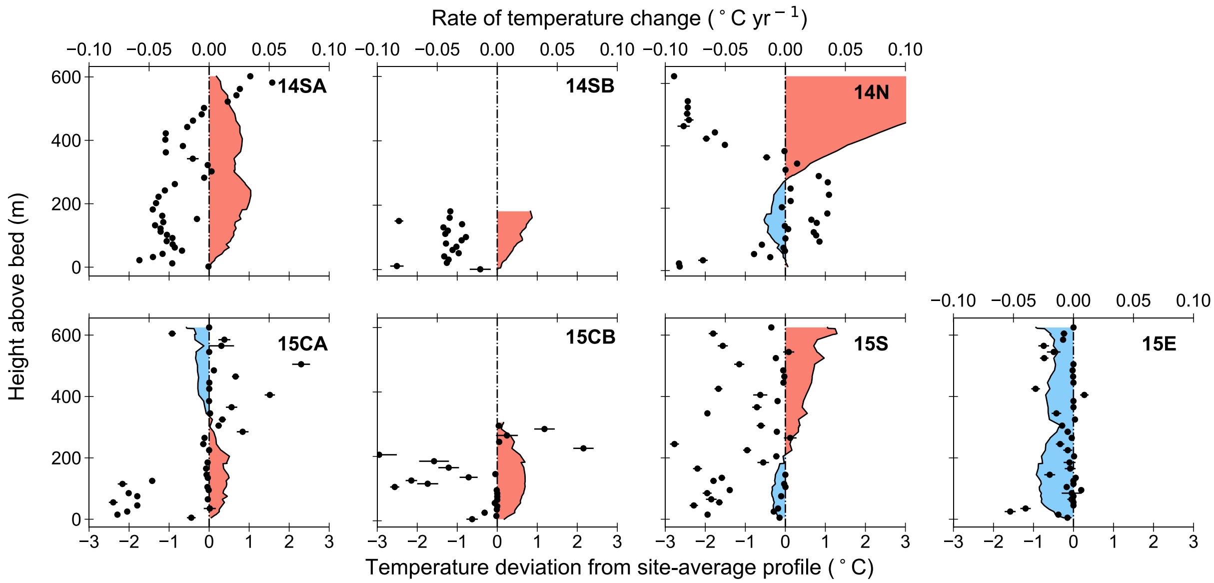

Figure 5: Rates of temperature change for each borehole (black dots) plotted with temperature deviations within each borehole from the site-average temperature profile. Red shaded regions indicate that the temperature profile of that borehole is warmer than the site-average profile, and blue shaded regions show the temperature profile is colder than the site-average profile. Error bars on the calculated rates are the same as in Fig. 3.

Figure 6: Why is this black and white, colors would be more useful. Change "thick" to "wide". This is a strange graphic, why don't you just show the temperature iso-lines? Better (shorter) vertical label needed.

To make it more accessible for all viewers, we will leave this figure in black and white. We have made the label in panel C to make it easier to read. We don't only show the temperature isotherms because we want to explicitly illustrate how a process that injects heat into the ice leads to not only warming, but produces cooling at rates that can match those observed at our field site.

Updated figure and caption:

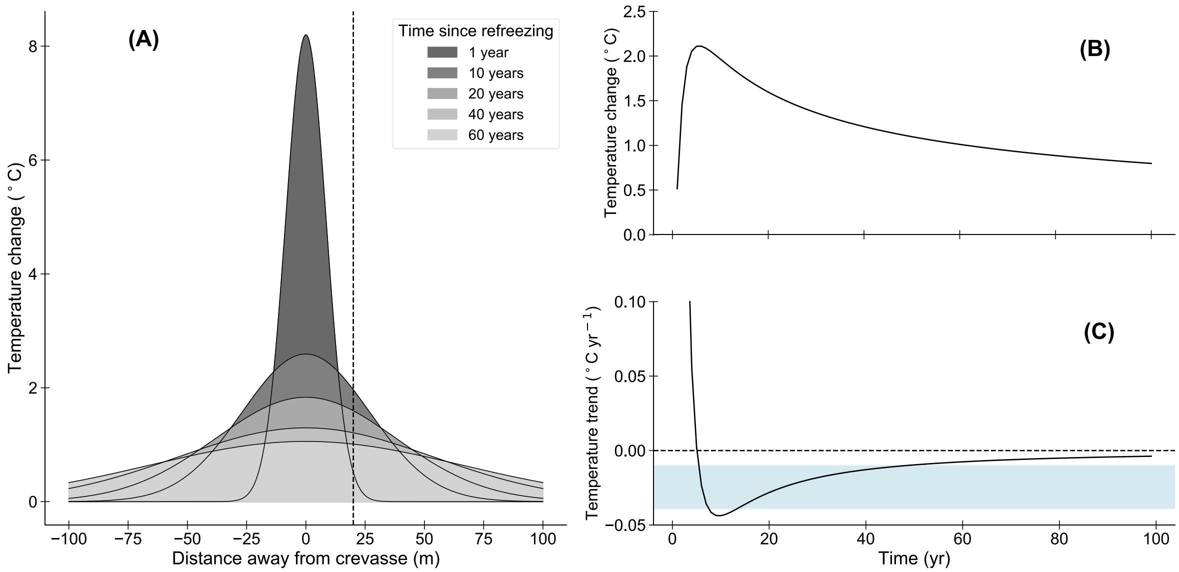

Figure 6: (A) Modeled changes in temperature after a crevasse 1 m wide refreezes. Darker colors show earlier times. Dashed line indicates a distance 20 m from the crevasse, which temperatures and temporal rates of temperature change are shown in B and C. (B) Changes in temperature over time at 20 m away from the basal crevasse. (C) Corresponding rates of temperature change for panel B. The blue shaded region shows the range of averaged rates of cooling in the lowest 100 m of the boreholes.

Figure 7: Use colors. What is the use of the main plot, the inset shows it all, just display the most important part.

We have enlarged the inset and only show that as we agree it is the most important part of the figure and should be prominently displayed. We experimented with various colormaps to cycle through and display the temperature field evolution, however, we believe that the greyscale evolution is easiest for readers to see.

Updated figure and caption:

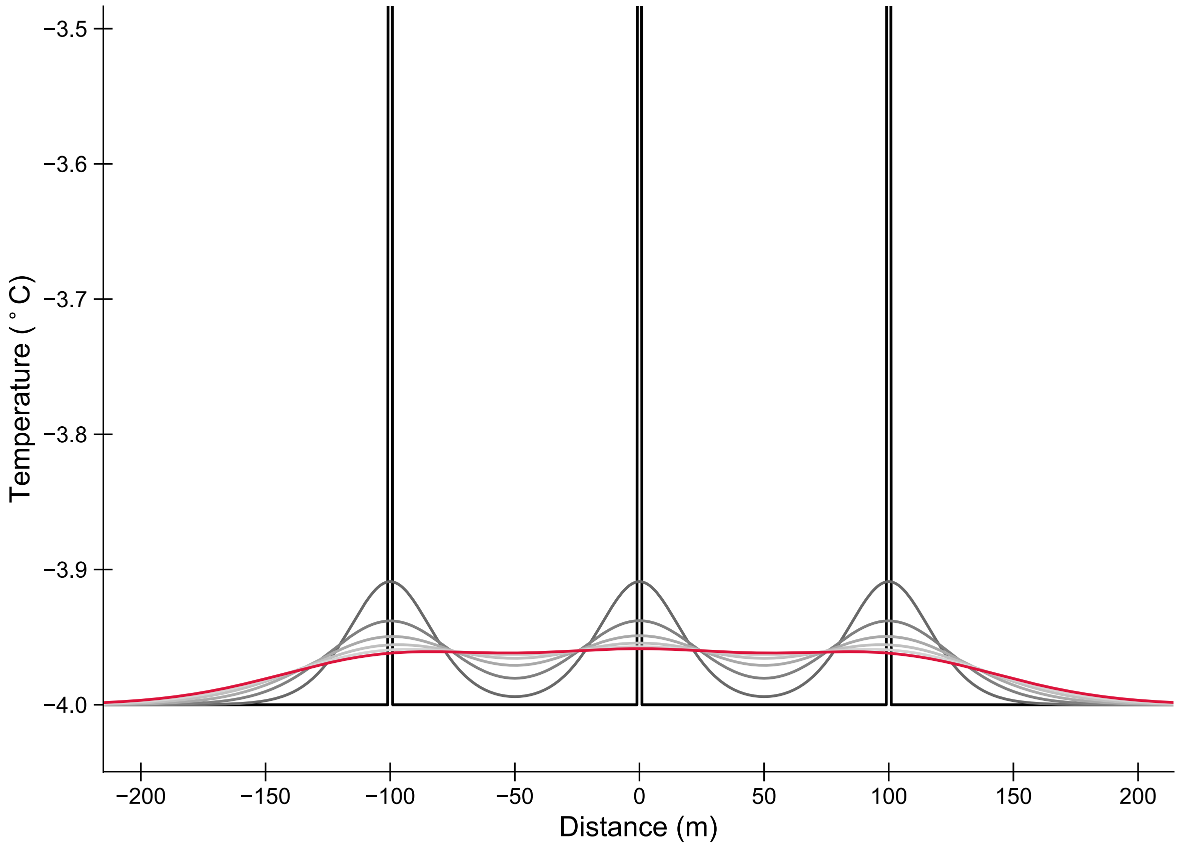

Figure 7: Evolution of a synthetic 1-D temperature field from 3 basal crevasses spaced 100 m apart. Temperatures are plotted every 5 years, and older temperature fields are shaded darker shades of grey. Red line shows the temperature field 30 years after refreezing.