Reply to Referee#2

May 3, 2023
Dr. Yukihiko Onuma
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Dear Referee#2,

We would appreciate a number of valuable comments very much. Please see enclosed our responses to all your comments as well as the revised marked-up manuscript entitled "Modelling the development and decay of cryoconite holes in Northwest Greenland" by Yukihiko Onuma et al. [Paper #egusphere-2023-54] submitted to the journal The Cryosphere. Our responses (**blue text**) to each of your comments (**black text**) were described on the following pages. We also described the revised sentences with the yellow marker following your suggestions.

Best regards,
Yukihiko Onuma and co-authors

RC2: 'Comment on egusphere-2023-54', Anonymous Referee #2, 20 Mar 2023

General statement:

The albedo of the Greenland Ice Sheet is of central importance to the surface energy budget. In the ablation area, the albedo is determined by whether debris is uniformly distributed or instead confined in cryoconite holes (CHs), so modeling the evolution of CHs is a worthwhile research project. The inputs to the model could be obtained from climate-model output. This paper could therefore be important, but in its current form it is difficult to read, so few readers will get through it.

The abstract could be improved by adding some key points, which are noted as they occur in the major comments below.

We would like to thank you very much for taking the time to review our manuscript. We are honored that you appreciate our project. According to suggestions from two reviewers, we have modified model code slightly and re-conducted numerical simulations including the sensitivity experiments. Accordingly, we have discussed about the results. The manuscript, figures and tables have been carefully revised to make those easier to understand the contents. The detailed our responses to your comments are as below.

Major comments:

(1) CHs develop because the albedo of cryoconite material (ac) is lower than the albedo of the surrounding bare ice (ai). It would therefore be good to explicitly examine the dependence of equilibrium CH depth on this difference (ai-ac), and add these results to the abstract.

Regarding the difference in albedo between ice surface and CH bottom (ai minus ac), you can confirm the difference from Figure 7(e, ai-exp). In the experiment, ac is constant of 0.1. The result indicates that CH tends to develop in the case of the greater difference between ai and ac as you know. Notably, the sensitivity tests showed that the CH depth does not equilibrate in any experiment cases at the studied glacier, where the meteorological conditions change before the depth reaches the equilibrium. It suggests that vertical dynamics of CHs mainly depends on not only the albedos but also meteorological conditions. According to your suggestion, we have added the point in Abstract and Section 5.2. (Lines 385-394).

Abstract:

Abstract. Cryoconite holes (CHs) are water-filled cylindrical holes with cryoconite (dark-coloured sediment) deposited at their bottoms, forming on ablating ice surfaces of glaciers and ice sheets worldwide. Because the collapse of CHs may disperse cryoconite on the ice surface, thereby decreasing the ice surface albedo, accurate simulation of the temporal changes in CH depth is essential for understanding ice surface melt. We established a novel model that simulates the temporal changes in CH depth using heat budgets calculated independently at the ice surface and CH bottom based on hole-shape geometry. We evaluated the model with in situ observations of the CH depths on the Qaanaaq ice cap in Northwest Greenland during the 2012, 2014, and 2017 melt seasons. The model reproduced well the observed depth changes and timing of CH collapse. Although earlier models have shown that CH depth tends to be deeper when downward shortwave radiation is intense, our sensitivity tests suggest that deeper CH tends to form when the diffuse component of downward shortwave radiation is dominant, whereas CHs tend to be shallower when the direct component is dominant, although CH depth is unlikely to be correlated with CH diameter. In addition, the total heat flux to the CH bottom is dominated by shortwave radiation transmitted through ice rather than that directly from the CH mouths when the CH is deeper than 10 mm. Furthermore, the tests highlight that the difference in albedo between ice surface and CH bottom is a key factor for accurately reproducing the timing of CH collapse and that positive feedback of lower ice surface albedo induces CHs collapse and therefore causing further lowering of the albedo. Notably, the sensitivity tests showed that the CH depth does not equilibrate in any experiment cases at the studied glacier, where the meteorological conditions change before the depth reaches the equilibrium. Heat component analysis suggests that CH depth is governed by the balance between the intensity of the diffuse component of downward shortwave radiation and the turbulent heat transfer. Therefore, these meteorological conditions may be important factors contributing to the recent surface darkening of the Greenland ice sheet and other glaciers via the redistribution of CHs. Coupling the CH model proposed in this study with a climate model should improve our understanding of glacier-surface darkening.

Lines 385-394:

The sensitivity experiments regarding the albedos of the ice surface and CH bottom (α_i-exp and α_c-exp) suggest that the difference between ice surface (α_i) and CH bottom albedos (α_c) is an important factor for reproducing the CH dynamics, especially the timing of CH collapse. The CH depth increases with an increase in α_i owing to decreasing M_i, whereas it decreases with an increase in α_c owing to decreasing M_c (Figs 9e and 9f). Notably, the sensitivity of the CH depth to α_i was greater than that to α_c. This is probably because shortwave radiation at the ice surface was greater than that at the CH bottom. In addition, α_i-exp suggests that a 0.1 decrease in α_i induces CH collapse one day earlier. Although α_c is known to be a key parameter for simulating the CH deepening rate (Podgorny and Grenfell, 1996), there is little information and discussions regarding α_i. Since we used constant values of α_c and α_i in α_i-exp and α_c-exp, respectively, our results highlight for the first time the importance of the difference between α_i and α_c in simulating vertical CH variations. CH tends to develop in the case of the greater albedo difference and vice versa.

(2) Equation 13. It is strange to compute the diffuse ratio under cloud from the net longwave at the surface, because the causality is backward: in reality the downward longwave is a consequence of cloud thickness.

As shown by van den Broeke et al. (2004), net longwave radiation at the surface becomes 0 under cloudy-sky conditions; whereas clear-sky condition can be recognized when net longwave radiation at the surface is negative and at a minimum for a given temperature. The reference has been added to the sentence of Eq. (13). (Line 130)

Reference:

van den Broeke, M., Reijmer, C., and van de Wal, R.: Surface radiation balance in Antarctica as measured with automatic weather stations, J. Geophys. Res., 109, D09103, doi:10.1029/2003JD004394, 2004.

(3) Eq. 15 (and other equations). These equations apply only to the center point of the CH. But parts of the bottom will still be in shadow for any nonzero solar zenith angle. There's no need to expand your calculations, but at least point out that you are ignoring this complication.

In response to Reviewer 1's comments about the zenith angles (major comments 1 and 2), we additionally conducted sensitivity tests to assess the sensitivity of the CH depth to solar zenith angle (θ_z-exp) and zenith angle of the edge from the centre of the CH bottom (θ_c-exp). Accordingly, we have updated Figure 7 (Figure 9 in the revised manuscript) and Table 3, and added discussion into Section 5.2 and 5.4.

Lines 111-115:

where D_{t-1} is the CH depth at one time step before (m), and ρ_w is the water density assumed equal to 1,000 kg m^{-3}. If the melt rate at the CH bottom is greater than that at the ice surface ($M_c > M_i$), the CH depth deepens, and vice versa. The initial depth D_0 at $t = 0$ in CryHo is a prescribed constant initial condition. Note that the heat balance at the CH bottom should vary on the position of the bottom such as the northern and southern edges. In this study, the heat balance at the center of the CH bottom was calculated for simplicity.

Lines 302-312:

We conducted sensitivity tests to assess the sensitivity of the CH depth to input data and model constants, such as air temperature (T_a-exp), radiation components (R_S-exp), initial depth (D_0-exp), hole diameter (ϕ-exp), albedo at the ice surface (α_i-exp), albedo at the CH bottom (α_c-exp), extinction coefficients of direct (κ_d-exp) and diffuse (κ_f-exp) radiation, solar zenith angle (θ_z-exp), and zenith angle of the edge from the centre of the CH bottom (θ_c-exp) (Table 3). Site-exp, i.e., Site 2 in 2014, was used as the control experiment for the sensitivity tests (Ctl-exp). The ranges of the changing parameters, which are summarized in Table 3, were determined based on field measurements (Table 2). The extinction coefficients for κ_d-exp and κ_f-exp were obtained from multiplying by factors of 0.25–4.00 the original values. The factor range was assumed by referring to the difference between the spectral flux extinction coefficient and absorption coefficient calculated from the imaginary refractive index of pure ice (Fig. 2). In R_S-exp, we assumed r_{dif} of Eqs (9) and (10) to be 0 and 1 in Sd and Sf cases shown in Table 3, respectively. In θ_z-exp and θ_c-exp, θ_z and θ_c calculated in the model were replaced with the values shown in Table 3, respectively, in order to quantify effects of the zenith angles on the CH depth.

Lines 427-439:

The sensitivity experiments regarding the zenith angle (θ_z-exp and θ_c-exp) suggest that differences in the zenith angles have little influence on the CH depth, except for the case of that the downward shortwave radiation always reaches the CH bottom from the hole mouth ($\theta_z = 0°$). θ_z-exp showed that the CH depth with a higher θ_z was shallower, owing to a decrease in M_c (Fig. 9i). In contrast, θ_c-exp showed that the CH depth with a lower θ_c was smaller (Fig. 9j). Notably, the experiments suggest that θ_z and θ_c hardly affect the CH depth in the case of over 15° and below 60°, respectively. Snell's law states that direct component of incident radiation is refracted through the air-water surface. The refraction angle is smaller approximately 20° than the incident angle θ_z by the law, therefore the direct component of the downward shortwave radiation more easily reaches the CH bottom from the hole mouth. However, such refraction is unlikely to affect the CH depth. Although the CryHo calculates M_c at centre of the CH bottom using θ_c, M_c may differ at the northern and southern edges of the CH bottom because the zenith angles of the edges of the CH bottom would differ from θ_c. θ_c-exp suggests that the CH depth is a temporary non-uniform in the northern and southern edges of the CH bottom. However, the CH depth is likely uniform again over time according to D_0-exp. Indeed, the simulated CH depth using the different θ_c converged within approximately two weeks (Fig. 9j). In addition, CHs observed in the studied glacier were flat on the CH bottom.

Lines 471-482:

Our model does not include the effect of water lingering in CHs on the heat balance at the CH bottom because a quantitative understanding of the mechanism of convective heat transport or the buffering effect in the lingering water is insufficient. Such lingering water in CHs may affect the heat exchange between the atmosphere and CH bottom. Heat exchange should not be negligible in the case of large water surfaces in CHs. Although water level in CHs is not estimated in the model, the refraction through air-water surface in CHs unlikely to affect CH depth in the studied glacier as discussed in θ_z-exp. However, the refraction might contribute to CH development in the lower latitude regions such as Asia, where the solar zenith angle is significantly smaller than that in polar region. In addition to the refraction, reflectance at the water surface would reduce amount of shortwave radiation reaching the CH bottom. To simulate CH depths globally, such an effect may have better been incorporated into CryHo. Besides lingering water in CHs, the thickness of cryoconite at the CH bottom, which is not considered by CryHo, is also likely to be a key factor in determining the CH diameter and shape (Cook et al., 2010). This is likely because a portion of the absorbed radiation in the cryoconite at the CH bottom could be transferred laterally and then melt the CH wall (Cook, 2012).

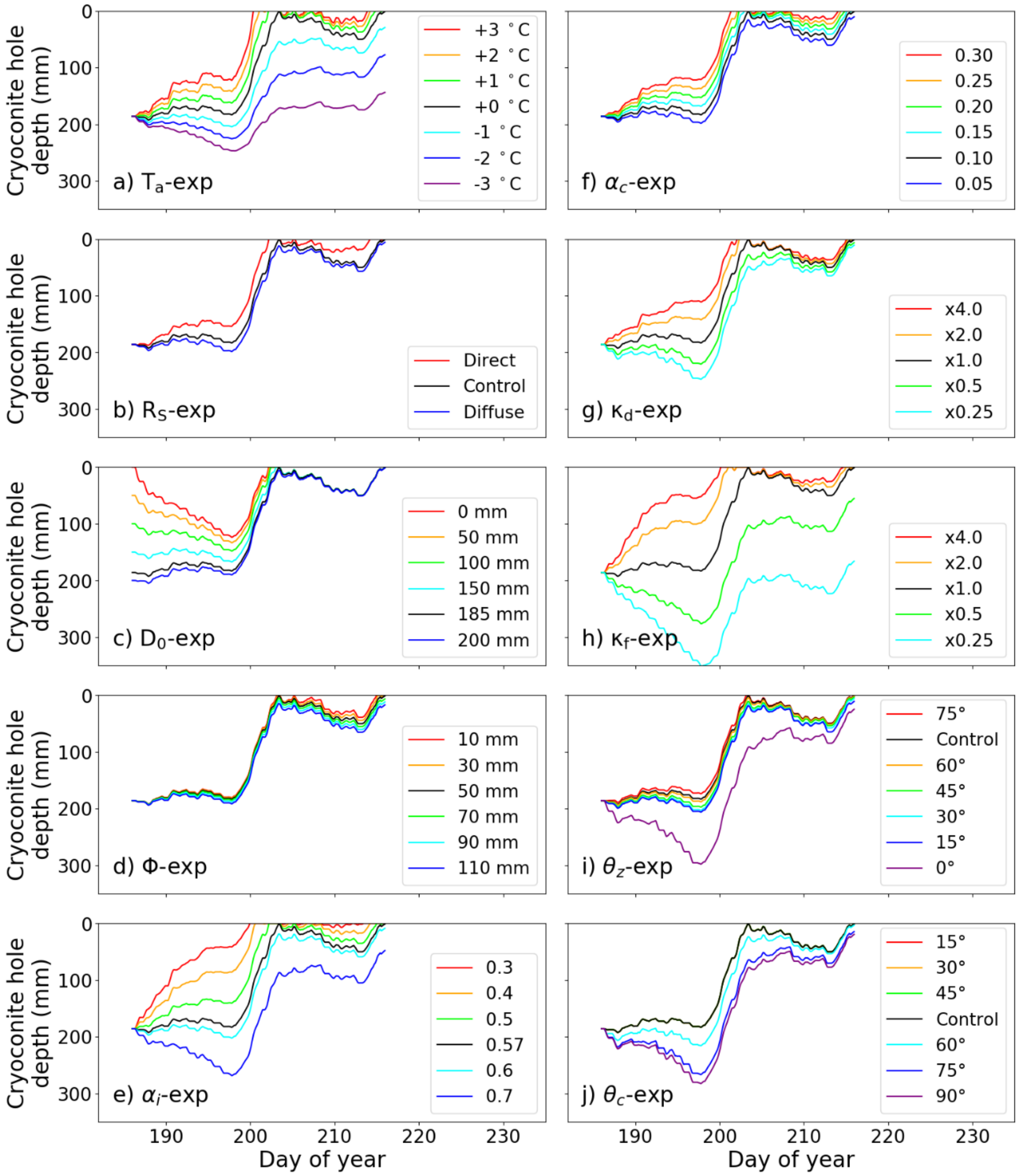

Figure 9: Sensitivity experiments of the temporal changes in cryoconite hole (CH) depth to model parameters and meteorological conditions at Site 2 in 2014. (a) Air temperature ($\boldsymbol{T_a}$-exp), (b) shortwave radiation ($\boldsymbol{R_S}$-exp), (c) initial CH depth ($\boldsymbol{D_0}$-exp), (d) CH diameter ($\boldsymbol{\phi}$-exp), (e) ice surface albedo ($\boldsymbol{\alpha_i}$-exp), (f) cryoconite albedo ($\boldsymbol{\alpha_c}$-exp), broadband flux extinction coefficient of ice for the (g) direct component ($\boldsymbol{\kappa_d}$-exp) and (h) diffuse component ($\boldsymbol{\kappa_f}$-exp), (i) solar zenith angle ($\boldsymbol{\theta_z}$-exp), and (j) zenith angle of the edge from the centre of the CH bottom ($\boldsymbol{\theta_c}$-exp). Black lines in each figure indicate the control experiment ($\boldsymbol{Ctl}$-exp). Note that lines for 15, 30 and 45° in the bottom right panel in the figure (j) are overlapped with the line for Control.

(4) Eq. 20 and elsewhere. The factor of 1000 is distracting, and it is not necessary; the user just needs to keep track of the units of k and D.

We have unified the unit of D to "m" throughout the whole of Section 2.

(5) Equation 21 for RStfc is wrong, because the path length of diffuse transmission into ice is taken to be just the vertical distance (as pointed out on lines 155-156). Instead you need to use the diffusivity factor (for example Liou 1980 p 97 eq 4.26): The effective path length for diffuse flux is the product of the vertical distance and the average secant for diffuse radiation, which varies with depth, but is often taken to be the secant of 53 degrees, i.e. 1.66.

Reference:

Liou, K.N., 1980: An Introduction to Atmospheric Radiation. Academic Press.

In Eq. (21), we parameterized the broadband flux extinction coefficient of bare ice based on spectral flux extinction coefficients experimentally determined by Cooper et al. (2021) for ice on the GrIS. Cooper et al. (2021) measured the vertical profile of the spectral flux extinction coefficients for the diffuse component of shortwave radiation, by which we parameterized the value of κ_f as a function of ice thickness x. Therefore, it is not necessary to multiply the depth by 1.66 for the vertical depth of bare ice in Eq. (21).

On the other hand, we noticed from your comment that the approximated value 1.66 should be used to obtain κ_d from κ_f. We do not know the exact values of κ_d. Considering a path length x, transmittance of the direct component of downward shortwave radiation (T_d) is described as follows:

$T_d = \exp(-\kappa_d * x)$

Since the effective optical path length for the diffuse component can be approximated as $1.66x$, the below relationship is derived.

$\kappa_f x \sim \kappa_d 1.66x$

Therefore, T_d is described as follows:

$T_d = \exp(-\kappa_f x/1.66)$

Hence, we have revised the relationship between κ_d and κ_f as:

$\kappa_d = \kappa_f/1.66$, (Equation (29) in the revised manuscript).

Accordingly, all numerical simulations have been re-conducted. Based on the results, we have revised the discussions in the manuscript. In addition, supplemental text for parameterization of the extinction coefficient has been moved to the main text according to Reviewer 1's suggestion.

Lines 232-234:

The coefficient r_d was assumed to be 1/1.66. The value 1.66 is used as an approximation value of the effective optical path length when the transmittance of diffuse component of shortwave radiation is obtained from that of direct component of shortwave radiation (Liou, 1980). Based on the assumption, κ_d was obtained by dividing κ_f by 1.66.

(6). Lines 320-324 point out that the CH depth is uncorrelated with CH diameter. This is an important result which should be included in the abstract.

The result has been added to Abstract. (Line 21)

(7) Lines 334-336. The positive feedback of low ice-albedo (ai), causing CHs to collapse and therefore causing further lowering of ai, is important and should be included in the abstract.

The positive feedback has been described in Abstract. (Line 25)

(8) Line 332: "Our results highlight for the first time the importance of both ai and ac". The key variable is probably neither ai nor ac, but rather their difference (ai-ac). It would be good to add a figure plotting equilibrium depth versus (ai-ac) for the standard values of other inputs. This is related to comment (1).

As our response to comment (1), we have emphasized the importance of the difference in Abstract and Section 5.2. (please see our response to your major comment (1)).

(9) I cannot make sense of lines 341-348; they need to be rewritten. For example, I don't understand "the direct component of shortwave radiation is transmitted throughout the ice rather than the diffuse component." Also, how can "diffuse" be "direct", as in this statement: "The CH bottom is directly accessible by a part of the diffuse component."

We have carefully revised the text to clarify the contents. (Lines 403-410)

Lines 403-410:

The sensitivity experiments regarding the broadband extinction coefficients of shortwave radiation transmitted throughout ice for the direct and diffuse components (κ_d-exp and κ_f-exp) suggest that κ_f is more effective at the CH depth than κ_d. Both experiments showed that the CH depth with a higher coefficient was shallower, owing to a decrease in M_c (Figs 9g and 9h); however, there was a significant difference in the sensitivity to the coefficients. One of the reasons is probably that κ_d is lower than κ_f, as in Eq. (29). Figure 10 showed that the diffuse component of shortwave radiation reaching the CH bottom was greater than the direct component of that even though κ_f is higher than κ_d, suggesting that the diffuse component of shortwave radiation reaches the CH bottom more easily than the direct component. Indeed, Figure 11 indicates that the reaching fraction of direct component of shortwave radiation transmitted throughout the ice to the CH bottom decreases with θ_z.

(10) Lines 370-371. The observation that CHs decay under overcast cloud is probably not because of the diffuse nature of the incident radiation. Under a cloud, the total downward shortwave is dramatically reduced, which means that turbulent fluxes become a larger fraction of the total energy budget, leading to CH decay.

The sentence has been modified as you suggested. (Lines 450-455)

Lines 450-455:

Takeuchi et al. (2018) suggested that CHs tend to be shallower under both cloudy and windy conditions. Our analyses also suggest that windy conditions are important meteorological conditions governing the CH decay (Figure 13a). Because the total downward shortwave is reduced through clouds although the diffuse component of downward shortwave radiation generally increases under cloudy condition, turbulent fluxes are likely to be dominant to the total energy budget, resulting in that the ice surface melts faster than the CH bottom. This is probably the reason why the CH collapse events were observed under cloudy conditions.

(11) Figure 1b. Only part of the CH bottom is shaded; the rest is sunlit.

Diffuse component of downward shortwave radiation was missing in Figure 1. So, we have added the lines for diffuse component of downward shortwave radiation into the figure. (Figure 1)

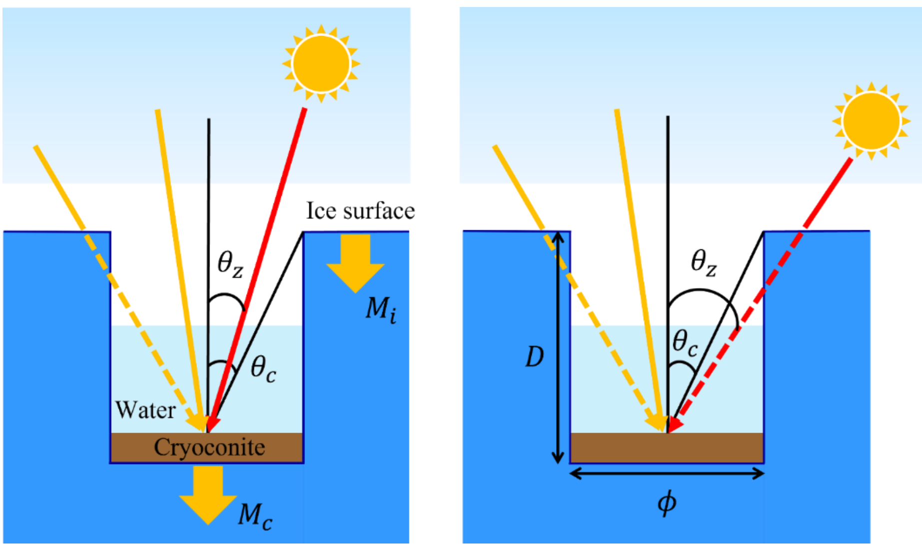

Figure 1: Concept of the cryoconite hole model (CryHo). Heat balances at the surface and cryoconite hole bottom are independently calculated (left). Red and orange arrows indicate direct and diffuse components of shortwave radiation, respectively. Cryoconite hole (CH) geometry, with depth (***D***) and

diameter ($\boldsymbol{\phi}$) being considered for distinguishing the direct component of shortwave radiation (right). Cryoconite thickness at the CH bottom is assumed to be zero in the model. The difference between the melt rate at the surface ($\boldsymbol{M_i}$) and that at the CH bottom ($\boldsymbol{M_c}$) changes the CH depth. The direct component of solar radiation can reach the CH bottom from the hole mouth if the solar zenith angle $\boldsymbol{\theta_z}$ is smaller than the zenith angle of the CH edge $\boldsymbol{\theta_c}$ (left, red solid arrow), while it is transmitted through the ice if the solar zenith angle is greater than the zenith angle of the CH edge (right, red dashed arrow). The diffuse component of downward shortwave radiation can reach the CH bottom regardless of $\boldsymbol{\theta_z}$ (orange solid and dashed arrows).

(12) Figure 3 is completely mysterious to me, so it needs to be redrawn. The long dark bars (apparently meaning LH?) extend on both sides of zero; what does that mean? The long dark bars are shaded where they are above zero; what does that mean? Some of the long dark bars have a short gap just below the zero line, then they continue as a tiny black box below the gap; what does that mean? What are the short dark bars at the top of some of the bars? Which bars are net radiation?

Figure 3 has been redrawn to clarify each bar. In addition, the explanation of the positive sign of each energy flux in the figure has been added to the figure caption. The positive sign of each energy flux means a downward component. Figure S5 has been merged with Figure 3 (Figure 5 in the revised manuscript) following Reviewer 1's comment.

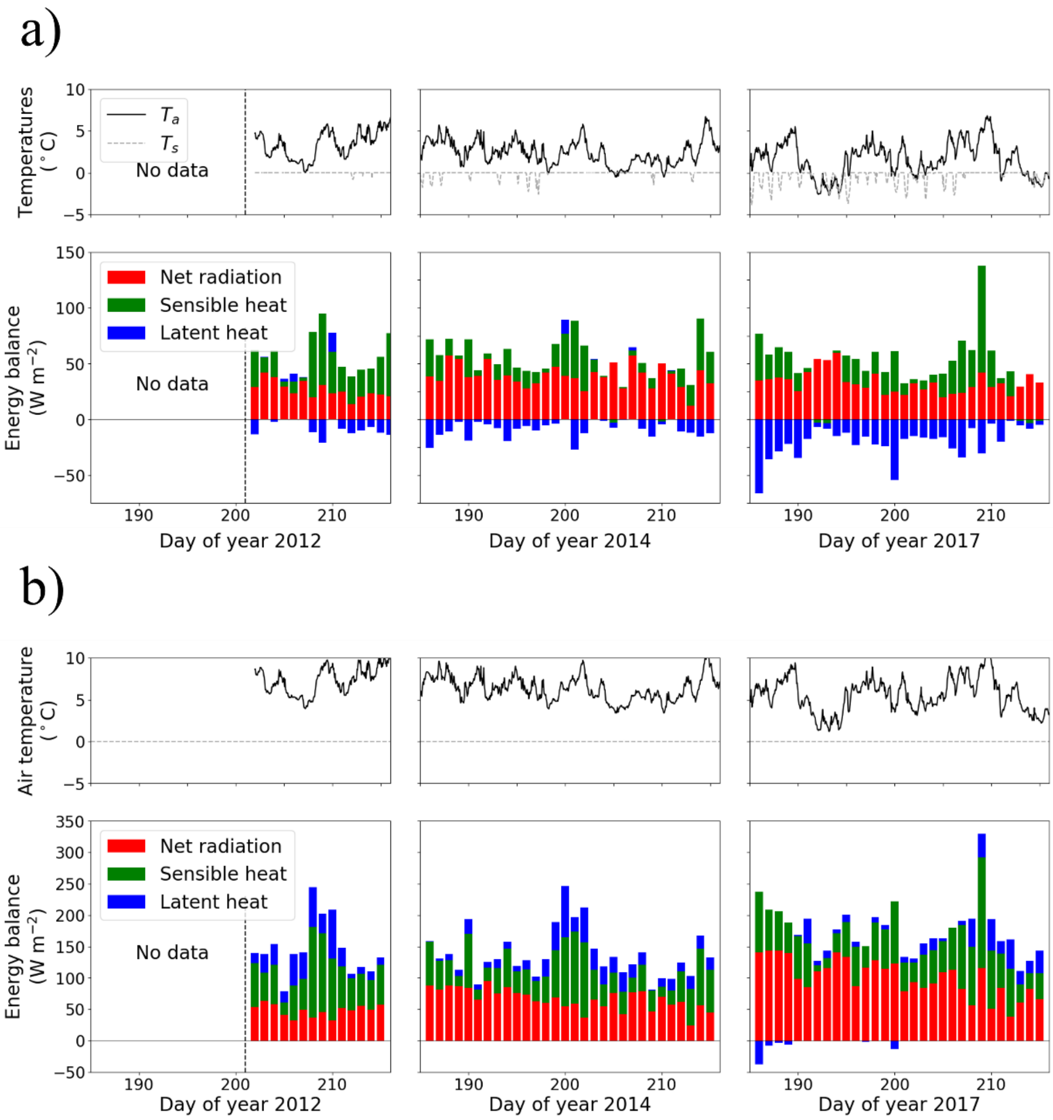

Figure 5: (a) Hourly air and surface temperatures ($\boldsymbol{T_a}$ and $\boldsymbol{T_s}$ in the upper panels, respectively) and daily surface energy balance (lower panels) at the Sigma-B site (Site 5 in this study) on the Qaanaaq ice cap during the 2012, 2014, and 2017 summer seasons from left to right, respectively. (b) Hourly air temperature (upper panels) and daily surface energy balance (lower panels) at Site 2. $\boldsymbol{T_s}$ shown in the upper panels in the figure (a) is calculated from the downward and upward longwave radiations. $\boldsymbol{T_a}$ shown in the upper panels in the figure (b) is corrected from $\boldsymbol{T_a}$ in the figure (a) and an observed lapse rate. Daily surface energy balance is calculated with CryHo. The positive sign of each energy flux means a downward component.

(13) The paper is difficult to read, partly because the reader needs to keep track of the non-intuitive subscripts on the variables. Unfortunately, I don't have useful suggestions on what to do about this.

According to the comment from Reviewer 1, we have listed alphabetically each symbol shown in Table 1 in order to easily trace each variable and constant used in this study. In addition, the supplemental text has been moved to the main text.

Minor comments:

Line 49. Is “bare ice” uncontaminated, or does it contain distributed cryoconite material?
Cryoconite particles are distributed on bare ice. The ice surface is known as dirty bare ice. Reviewer 1 suggested that bare ice should be divided into two types: dirty bare ice and clean bare ice, so the sentence has been modified (Lines 53-55).

Lines 53-55:
Topologically heterogeneous ice surfaces can be classified into four types: clean bare ice surfaces, dirty bare ice surfaces, surfaces with CHs, and meltwater streams (Irvine-Fynn and Edwards, 2014; Chandler et al., 2015; Holland et al., 2019; Tedstone et al., 2020).

Line 76. “latent heat flux”. Point out that HLi is restricted to the latent heat of evaporation; it does not include the latent heat of melting.
The explanation has been added. (Lines 80-85)

Lines 80-85:
where α_i is the ice surface albedo (dimensionless), R_S is the downward shortwave radiation (W m^{-2}), R_{Lni} is the net longwave radiation (W m^{-2}), H_{Si} is the sensible heat flux (W m^{-2}), H_{Li} is the latent heat flux (W m^{-2}), ε is the emissivity of the snow/ice surface, which is assumed to be 1.0 (dimensionless), R_L is the downward longwave radiation (W m^{-2}), σ is the Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), and T_i is the surface temperature (K). Subscript i used in the variables refers to the ice surface. All the downward components have positive signs. Note that H_{Li} is restricted to the latent heat of evaporation; it does not include the latent heat of melting.

Lines 79-80. “Heat conduction from the glacier ice . . . assumed to be negligible.” This is valid if Ta is never colder than Ts. Figure 3 shows that this condition holds during the summer: whenever Ta is negative, Ts likewise is negative and approximately equal to Ta. But in spring and autumn they might differ. This “Ts” in Figure 3 is probably what is called “Ti” in the text, neither of which is defined in Table 1.
Thank you for the comment. Ts was derived from the automatic weather station, so Ts differs from Ti, which is calculated in the CryHo. Ts has been added into Table 1.

Line 85. Give a reference for the value of bulk coefficient.

The coefficient is based on the below reference. The reference has been added to the sentence. (Line 90)

Reference:

Kondo, J.: Meteorology of water environment, Asakura Publishing, Tokyo, Japan, 1994.

Line 96 Eq 7 for Mc. The units don't match. LHS is mm/hour, but RHS is kg m^-2 hr^-1. The missing factor is density, kg m^-3.

Thank you for pointing out. The ice densities were missing in Eqs 5 and 7. The densities have been added to the Eqs 5 and 7. Accordingly, the units of Mi and Mc are modified in the manuscript.

$$Q_{Mi} = \max[0, Q_i], \quad (5)$$

$$M_i = \frac{t_h Q_{Mi}}{l_M \rho_i},$$

$$Q_{Mc} = \max[0, Q_c], \quad (7)$$

$$M_c = \frac{t_h Q_{Mc}}{l_M \rho_i},$$

Line 112. Change "distinguish" to "separate".

The word has been modified.

Line 121. Niwano et al. 2015 is missing from the reference list.

The reference has been added to the list.

Line 155. Change "pass length" to "path length".

The word has been modified. (Line 167)

Line 171. RSfd and RSfs are undefined; they do not appear in Table 1.

These terms were typos. Those terms have been modified to Rsd and Rsf, respectively. (Line 225)

Line 177. Eq (25). To say that rd=1.0 is equivalent to assuming that the incident radiation becomes rapidly diffused in the topmost millimeters of the ice, which is probably true.

As our response to your major comment (5), rd has been assumed to be 1/1.66 for the CryHo.

Line 236. “Lapse rate” is the rate of decrease of temperature with height. If temperature decreases with height, the lapse rate is therefore positive. So remove the minus-sign, unless you mean a temperature-inversion.

The minus-sign has been removed. (Line 291)

Line 428 says that KF designed the study, but then the next sentence says that it was instead YO, NT, and TA who designed the study.

The sentence has been modified to the below. (Lines 515-517)

Lines 515-516:

KF designed the study. YO, NT, and TA designed the field observations. KF developed the model with the support of MN and TA.

Table 1. Does C have units?

The C does not have a unit (non-dimension).

Figure 3 caption line 601, “Ts”. In Table 1 you instead use Ti.

Ts means surface temperature derived from the automatic weather station. The temperature is not used for the model simulations. Ts has been added to Table 1.

Figure 5. Depth and diameter have unnecessary zeros after the decimal points. For example, change 39.0 to 39.

The decimal points have been removed from Figures 5 and 6 (Figures 7 and 8 in the revised manuscript).

Figure 7a,f,g,h. Reverse the order of the legends to correspond with the order of curves. For example, in 7a the red curve is on top, so the legend should have the red legend (+3) on top.

The figure panels have been modified as you suggested (Figure 9 in the revised manuscript).

Figure S3. The horizontal azis is labeled theta-0. In the text it is theta-z.

The theta-0 has been changed to the theta-z (Figure S2 in the revised supplemental text).

Figure S6. Three of the plots are labeled “control”; what does that mean?

These plots have different components from each other. We have modified the labels in the figure legend. In addition, Figure S6 has been moved to the main text (Figure 10 in the revised manuscript).

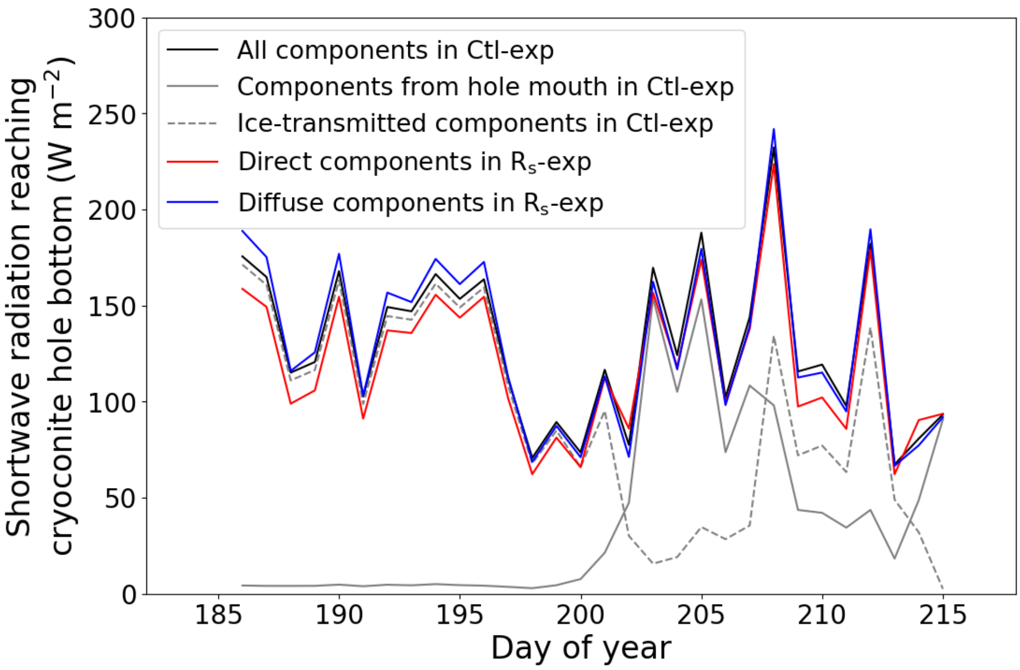

Figure 10: Daily mean temporal changes in direct and diffuse components of shortwave radiation reaching the cryoconite hole (CH) bottom in 2014. Blue and red lines indicate the direct (R_{sdt}+R_{stdc}) and diffuse (R_{sfct}+R_{stfc}) components in $\boldsymbol{R_S}$-exp, respectively. Black line indicates both component of shortwave radiation (R_{sdt}+ R_{sfct}+ R_{stdc}+R_{stfc}) in Ctl-exp. Grey solid and dashed lines indicate the radiation components reaching the CH bottom from the hole mouth (R_{sdt}+ R_{stdc}) and transmitting through ice (R_{sfct}+ R_{stfc}) in Ctl-exp, respectively.