Reply to Dr. David Chandler (Referee#1)

May 3, 2023
Dr. Yukihiko Onuma
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Dear Dr. Chandler,

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

RC1: 'Comment on egusphere-2023-54 (Yukihiko Onuma et al.)', David Chandler, 16 Mar 2023

I'd like to thank the authors for their efforts developing this new model for cryoconite hole depth, which is well presented along with useful sensitivity experiments and some validation. As the authors point out, changes in cryoconite hole dynamics can influence ice surface albedo – so this is an important topic, given that SMB is one of the key controls on Greenland's sea-level contribution. I imagine this model could easily be driven by either AWS data or climate model output, making it a useful tool for investigating how cryoconite holes could influence albedo under climate warming anywhere in Greenland or indeed Antarctica given some basic observations of typical hole dimensions (which are already available for many places). Other applications would include supraglacial hydrology (changes in water storage) and ice surface microbial processes.

The model calculates changes in hole depth by considering energy balance at the centre of the hole. Validation with some field observations yields an encouraging match overall, with some discrepancies as we would expect.

There are two important aspects which I think need to be considered further before publication, given the application of this model in regions with generally large zenith angles. On that basis I have ticked the major revisions box, but I'm hoping it's not a lot of work to implement these changes. Elsewhere there are some minor points requiring additional clarification, and the manuscript needs language editing by a native English speaker as there are numerous grammatical errors and a few sentences which are a little hard to follow. Apart from the language itself, the paper is clear and easy to follow.

I'm not very up to date with the relevant literature so I just reviewed this study on its own merits and not in relation to other recent work.

We would like to thank you very much for taking the time to review our manuscript. Since the cryoconite hole model (CryHo) could be driven by climate model output as you mentioned, the model has a potential to spatio-temporally evaluate albedo reduction caused by collapses of CHs in the Greenland Ice Sheet under climate change. According to the suggestions from you and another reviewer, we have modified model code slightly, re-conducted numerical simulations including the sensitivity experiments, and revised the manuscript. The detailed our responses to your comments are as below.

Main points

(1) Refraction is not considered when the direct SW component passes from air to water. I wonder if

that would change your conclusion that the diffuse component dominates over the direct component. If the zenith angle (in the air) is theta_a, and the refractive indices of air and water are n_a = 1 and n_w = 1.33, then the zenith angle in the water (theta_w) would be estimated from Snell's law, i.e.,

n_a * sin(theta_a) = n_w * sin(theta_w).

This is worth considering, since your range of zenith angles in air (noted as 56 to 85deg: Line 305) would become 38 to 48deg in water, so it's much more likely that the direct SW can reach the hole centre. You might also want to consider reflection by the water surface.

Refraction along the transmitted (air-ice-water) pathway would also be worth considering but I imagine would be harder to implement.

I think it would be quite easy to adjust the model to account at least for this air-water refraction and hopefully not a lot of work to re-run the plotting scripts so we can see if this is important or not.

Thank you for your constructive comments. As you pointed out, the air-water refraction of light might increase the amount of solar radiation reaching the CH bottom even when the solar zenith angle is larger, while the opposite effect would occur when the reflection of light at the water surface reduces the amount of that reaching the CH bottom. Since these two effects depend on water depth, it is difficult to incorporate the effect of the refraction and reflectance into the model, which does not simulate water level in CH. However, we additionally conducted a sensitivity test to the solar zenith angle (θ_z-exp) to discuss the effect of the zenith angle on the CH depth. The experiment showed that the solar zenith angle hardly affects CH depth in cases over 15° (Figure 9). This is probably due to that the direct component of downward shortwave radiation hardly reaches the CH bottom from the hole mouth in such cases. In the studied glacier, the solar zenith angle generally ranges from 56 to 85°, suggesting that the contribution of light refraction through air-water boundary to CH depth is insufficient. We add the result and discussion in Section 5.2 as well as the explanation about the sensitivity test in Section 4. The refraction may have better been considered to simulate CH depth globally because the solar zenith angle is sometimes below 20° in low latitudes such as Asia. This point has been raised in Section 5.4 as future challenge.

Regarding our conclusion that CHs tend to decay and develop in the case of that the direct and diffuse components are dominant, we have discussed the sensitivity of the CH depth to the shortwave radiation components in the paragraph for R_S-exp. Figures 9b and 10 in the revised manuscript showed that the CH tends to develop when the diffuse component is dominant. In the studied glacier, there is no significant difference between the direct and diffuse components reaching the CH bottom even at the time of meridian transit in the summer solstice (Figures 11a and 11c in the revised manuscript). The result suggests that the diffuse component relatively reaches CH bottom more than the direct component in the studied glacier. This may be one of the reasons why the diffuse component contributes to CH development rather than the direct component in R_S-exp. We have added the result of $R_{Sc}D$-exp and $R_{Sc}\phi$-exp in the higher θ_z case (Figure 11) and the discussion in Section 5.2.

Lines 302-318:

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 were forced to be replaced with the values shown in Table 3, respectively, to quantify effect of the zenith angles on the CH depth.

To quantify the four components of shortwave radiation reaching the CH bottom (R_{Sdc}, R_{Sfc}, R_{Stdc}, and R_{Stfc}) for different CH geometries (i.e., depths and diameters), we conducted two sensitivity tests ($R_{Sc}D$-exp and $R_{Sc}\phi$-exp, respectively) at 13:00 and 1:00 local time on DOY 172 (i.e., the time of meridian transit and mid-night at the summer solstice) in 2014. The CH depth and diameter ranged from 10 to 350 mm in $R_{Sc}D$-exp and from 10 to 150 mm in $R_{Sc}\phi$-exp, respectively. The CH diameter and depth were assumed to be 50 mm in $R_{Sc}D$-exp and 10 mm in $R_{Sc}\phi$-exp, respectively. The other model constants were the same as those in Ctl-exp.

Lines 355-370:

The sensitivity experiment regarding the shortwave radiation components (R_S-exp) suggests that CHs tend to decay and develop in the cases where the direct and diffuse components are dominant, respectively (Fig. 9b). We then compared the contributions of each radiation component reaching the CH bottom during the experiment period (Fig. 10, red and blue lines). The CH bottom is more accessible by the diffuse component ($R_{Sfc} + R_{Stfc}$) rather than the direct component ($R_{Sdc} + R_{Stdc}$), except for shallowing depth case. In the model, the direct component of shortwave radiation can reach the CH bottom only when the solar zenith angle θ_z is smaller than the CH edge θ_c (Fig. 1 and Eq.

15) and it is transmitted through the ice in the opposite case. Because θ_z and θ_c ranged from 56 to 85° and 8 to 90° during the simulation period at the studied glacier, respectively, the direct component reaching the CH bottom from the hole mouth was very limited. Figure 11a showed that there is no significant difference between the direct and diffuse components reaching the CH bottom even at the time of meridian transit in the summer solstice, suggesting that the diffuse component relatively reaches CH bottom more than the direct component in the studied glacier. To investigate heat flux to the CH bottom by shortwave radiation from the hole mouth or through the ice, we additionally compared the contributions of each radiation component reaching the CH bottom (Fig. 10, grey lines). The figure depicts that the radiation components transmitted through ice to the CH bottom ($R_{Stfc} + R_{Stdc}$) was greater than the radiation components reaching the CH bottom from the hole mouth ($R_{Sfc} + R_{Sdc}$) when CH developed from DOY 208 to 213, meaning that radiation components transmitted through ice are also important for the heat balance at the CH bottom (i.e., Q_c). Further discussion regarding shortwave radiation transmitted throughout the ice is described later.

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 471-479:

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 effects may have better been incorporated into CryHo.

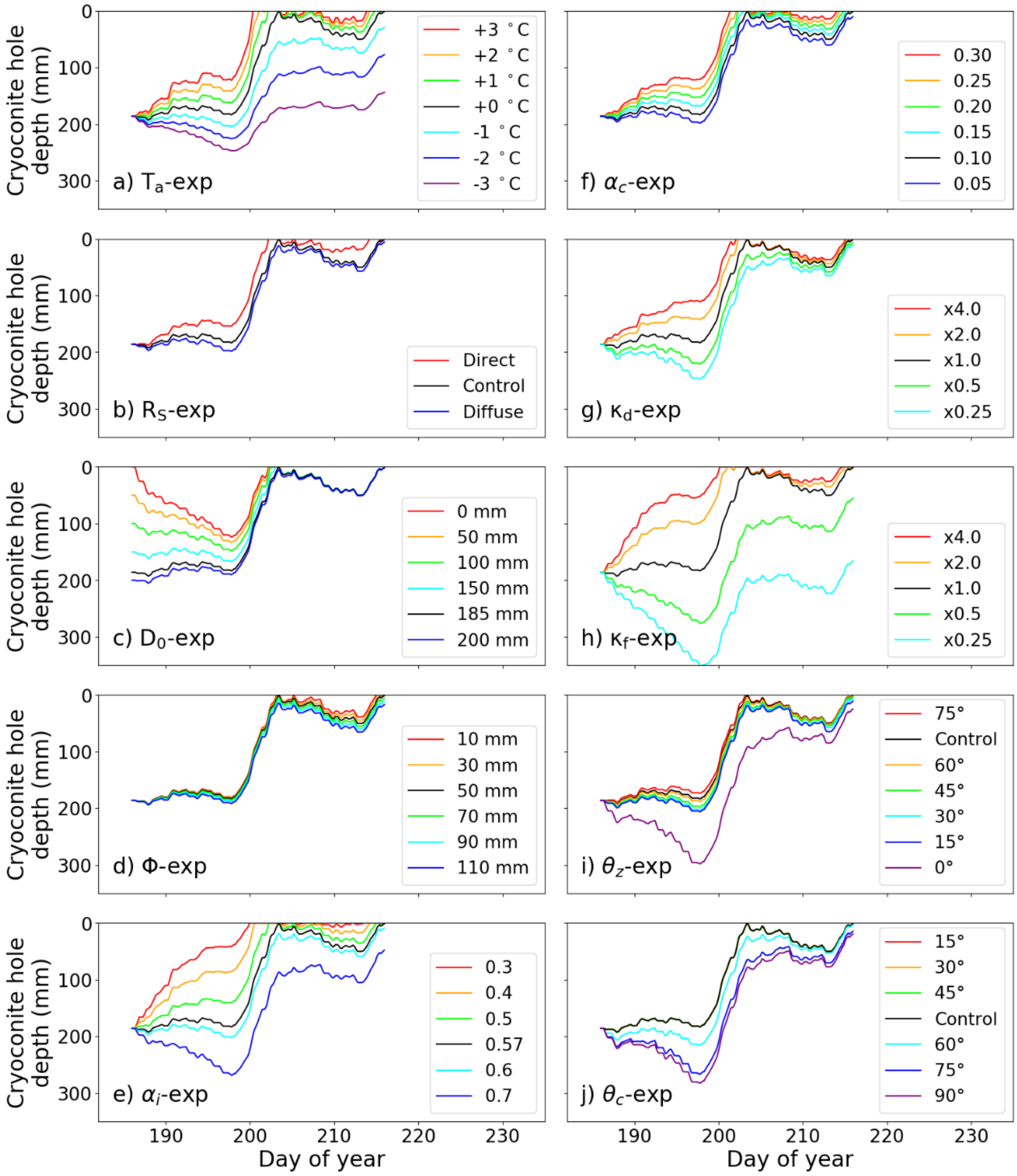

Figure 9: Sensitivity experiments of the temporal changes in cryoconite hole (CH) depth to model parameters and meteorological conditions at Site 2 in 2014. (a) Air temperature ($\boldsymbol{T_a}$-exp), (b) shortwave radiation ($\boldsymbol{R_S}$-exp), (c) initial CH depth ($\boldsymbol{D_0}$-exp), (d) 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.

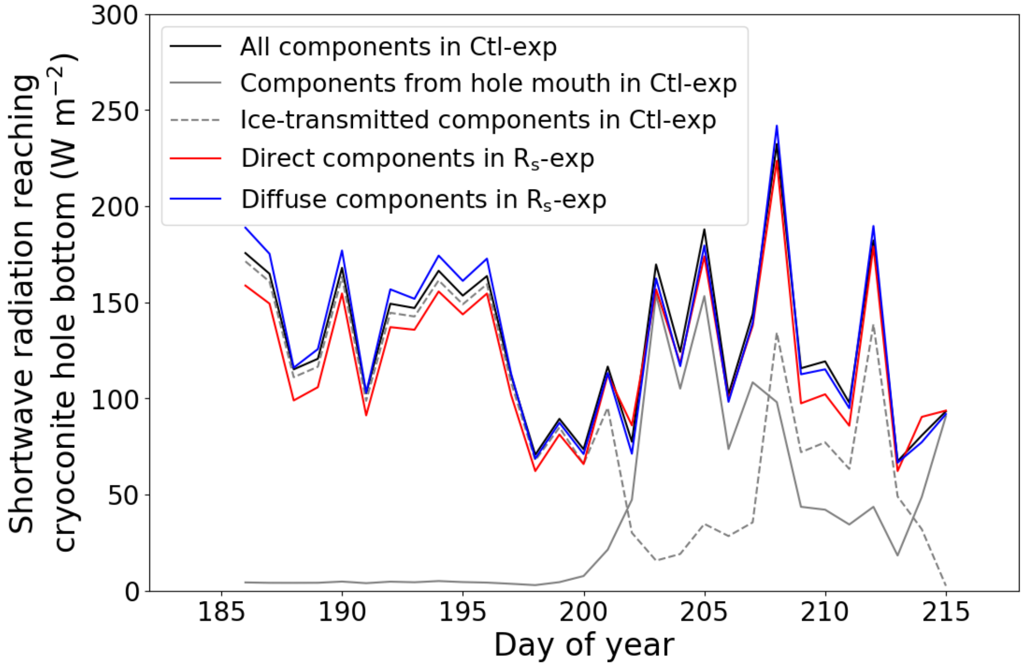

Figure 10: Daily mean temporal changes in direct and diffuse components of shortwave radiation reaching the cryoconite hole (CH) bottom in 2014. Blue and red lines indicate the direct (R_{sdt}+R_{stdc}) and diffuse (R_{sfct}+R_{stfc}) components in $\boldsymbol{R_S}$-exp, respectively. Black line indicates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

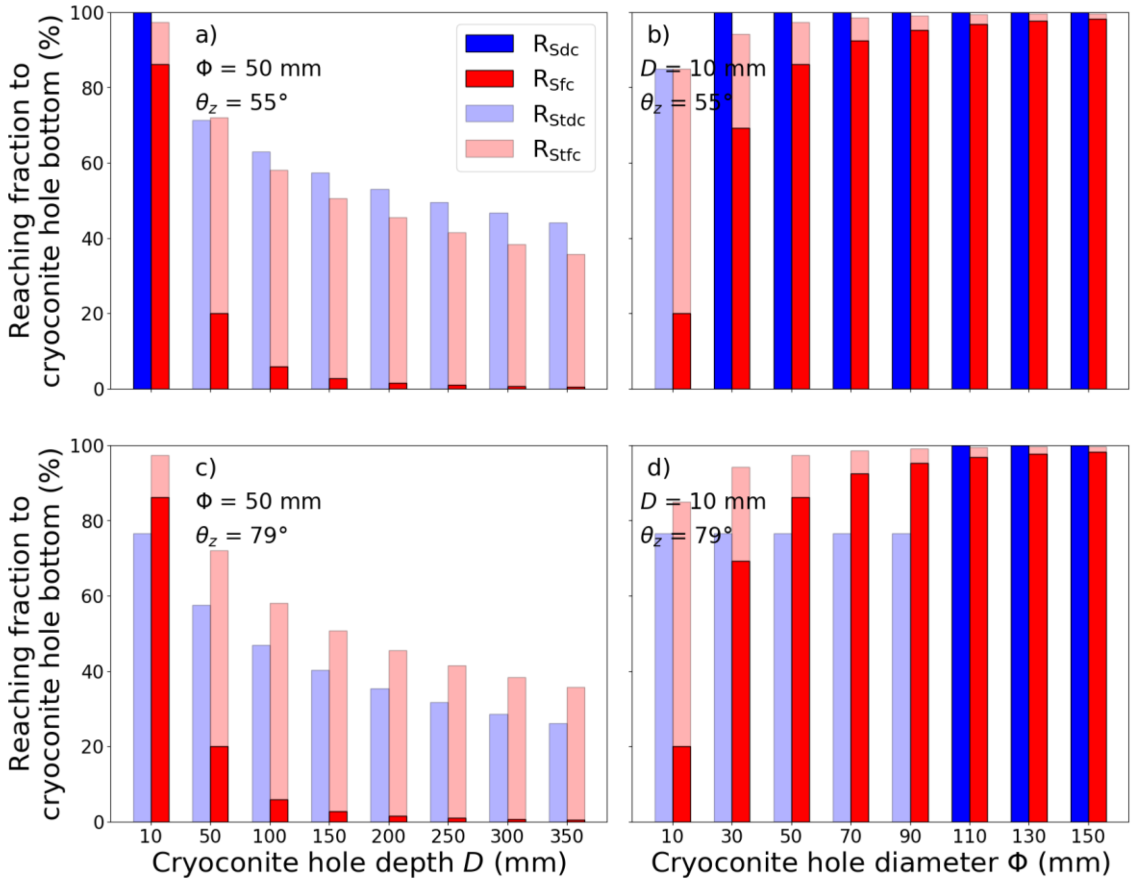

Figure 11: Sensitivity experiments of the cryoconite hole (CH) geometry on the direct and diffuse components of shortwave radiation reaching the CH bottom for (a, c) CH depth and (b, d) CH diameter. Dark blue and red bars in the figure indicate the direct and diffuse components of shortwave radiation, respectively. Light blue and red bars indicate the direct and diffuse components of shortwave radiation transmitted throughout ice, respectively. The vertical axis represents the fraction of direct and diffuse components against the incoming shortwave radiation at the ice surface (100 % at the ice surface). The ratios were derived from numerical simulations with different CH depth or CH diameter on day of the year (DOY) 172 in 2014. The meteorological conditions for the simulations were assumed to be those at 14:00 local time (a, b) and 1:00 local time (c, d) on the date used for Ctl-exp.

(2)Only melt at the hole centre is considered. This makes sense from the validation perspective as the measurements were collected at the centre. However, in Greenland or Antarctica as the sun goes round and round quite low in the sky it is plausible the hole centre is never directly illuminated but that the outer parts are illuminated directly for several hours. I think the two 'extremes' to quantify this would be the northern and southern edges of the hole bottom. Could some of the melt rates be repeated for these locations, with a simple adjustment to the geometry calculation? If it turns out the melt rate is actually quite uniform across the bottom of the hole, that would itself be an interesting result as it would compare well with the generally flat hole bottoms and would support the model simply being applied to the centre and not the edges. This is related to the first point, since if the diffuse component is dominant then the melt rate should be quite uniform. On the other hand if the direct component has been underestimated then the melt rate could vary quite considerably across the hole bottom.

If the phenomenon pointed out by the reviewer occurs, the surface of CH bottom and the thickness of the cryoconite in the hole would be non-uniform. We guess that the non-uniformity causes positive feedback, resulting in the CH bottom being further non-uniform. Previous study suggests that topological conditions affect the CH geometry on steep north-sloping ice (Cook et al., 2018). However, the effect should be negligible because CHs observed in the studied glacier, where the slope is below 5°, were flat on the CH bottom.

To discuss the effects of the northern and southern edges of the CH bottom on the CH depth, we also conducted the sensitivity test of the CH depth to zenith angle of the edge from the centre of the CH bottom (θ_c-exp). The experiment showed that θ_c hardly affects CH depth in the case of below 60 degrees (Figure 9 in the revised manuscript). The sensitivity test of the CH depth to initial depth (D_0-exp) suggests that the CH bottom is relatively accessible by shortwave radiation in the case of shallower depths, and vice versa, resulting in that the CH depth converge over time. Although the CH depth may be a temporary non-uniform in the northern and southern edges of the CH bottom, the CH depth is likely uniform again over time.

The above points have been described in Sections 5.2 and 5.4. Regarding the revised sentences, please see our response to your major comment (1). In Section 2.2, we have described that the model calculates the heat balance at centre of the CH bottom (Qc).

Reference:

Cook, J. M., Sweet, M., Cavalli, O., Taggart, A., and Edwards, A.: Topographic shading influences cryoconite morphodynamics and carbon exchange, Arct. Antarct. Alp. Res., 50, S100014. https://doi.org/10.1080/15230430.2017.1414463, 2018.

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.

Other points.

Hole widening: I don't think this is specifically mentioned. However, the direct component is sensitive to hole diameter (because of shading) so it's certainly worth some discussion even if not included in this first version of CryHo. Later versions should probably attempt to track both the hole depth and the diameter. Is there some positive feedback? As the hole gets wider, more and more of the vertical wall gets illuminated, presumably causing further widening, and additionally a greater water surface area for turbulent heat transfer (noting the area increases as diameter^2 while the wall circumference for melting only increases linearly with diameter). As the hole widens, the bottom is also less shaded. Could that explain how cryoconite holes can sometimes grow quite large, eventually coalescing? Hole widening might mitigate collapse, to some extent, if it can help to increase depth.

Our sensitivity experiment (ϕ-exp) suggests that the difference in hole diameter has little effect on hole depth. Furthermore, previous studies suggest that CH diameter is uncorrelated to CH depth (Gribbon, 1979; Cook, 2012). Cook (2012) formulated thermal energy directed to the hole walls. However, his observation in the Arctic region suggests that the CH diameter is not correlated with the CH depth but correlated with the thickness of cryoconite at the CH bottom. Therefore, the positive feedback suggested by the reviewer is unlikely to occur. On the other hand, Cook (2012) suggests that a portion of the absorbed radiation in the cryoconite at the CH bottom could be transferred laterally and then melt the CH wall. By incorporating the effect of the lateral heat as well as sensible heat in the water on the CH diameter into CryHo, temporal change in the CH diameter might be calculated.

The discussion regarding the feedback and the lateral heat has been described in Sections 5.2 and 5.4.

Reference:

Cook, J.: Microbially mediated carbon fluxes on the surface of glaciers and ice sheets. PhD Thesis, University of Sheffield, UK, 2012.

Lines 377-384:

Figure 11b suggests no significant difference in the total shortwave radiation reaching the CH bottom among the different diameters, thereby supporting the ϕ-exp result. Indeed, no significant correlation between the CH depth and diameter has been found (Gribbon, 1979; Cook, 2012). Since an increase in CH diameter cause more direct shortwave radiation reaching the CH bottom, positive feedback of the CH development is possible. However, such feedback is unlikely to occur because Figures 11b and 11d suggest that most of the diffuse component of the transmitted shortwave radiation reaches the CH bottom over 30 mm in CH diameter in the case of 10 mm depth. Furthermore, the observed CH depths and diameters significantly varied among the sites and years (Table 2), suggesting that CH depth is mainly controlled by factors other than the CH diameter.

Lines 479-482:

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).

L25: "wind speed". Technically should this be the turbulent heat transfer (which of course is a function of wind speed, but also other factors such as roughness, humidity, air temp etc).

The term has been modified to turbulent heat transfer. (Line 28)

L40-50: Our study from west Greenland also reported CH collapse and debris dispersal following warm/windy conditions (Chandler et al. 2005 TC; our Section 3.1). Also note we used four bare ice types rather than three (clean ice, dirty ice, CH, water).

Chandler et al. (2015) have been added (Line 47) because we think that Chandler et al. (2005) is a typo. The surface types have been changed to four types (Lines 53-55).

Lines 45-47:

CH collapse events have also been reported in Svalbard and Southwest Greenland (Hodson et al., 2007, 2008; Stibal et al., 2008; Irvine-Fynn et al., 2011; Chandler et al., 2015), while it has been indicated that a higher melt rate at the ice surface induces CH collapse (Hodson et al., 2007).

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).

Section 2: throughout the paper it would be better to write the equations in SI units, to avoid awkward conversion factors, even if you have used these other units in the model code for convenience.

We have unified the units to SI units throughout the whole of Section 2.

Eq 7: Mc = t_h * Q_Mc / l_M … the units don't balance here, I think there is a rho missing? Please could you double check all the equations for typos / consistent units (I haven't checked all of them).

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

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

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

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

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

Eq 9-10: A diagram showing the ray paths of the four SW components would be handy here – maybe add a panel to Fig 1?

The diffuse component of shortwave radiation has been added to Figure 1 following your suggestion.

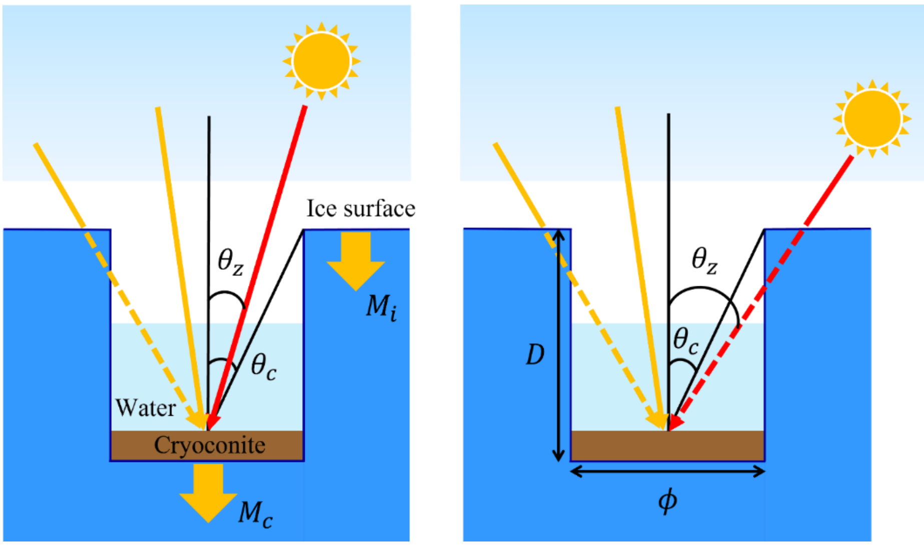

Figure 1: Concept of the cryoconite hole model (CryHo). Heat balances at the surface and cryoconite hole bottom are independently calculated (left). Red and orange arrows indicate direct and diffuse components of shortwave radiation, respectively. Cryoconite hole (CH) geometry, with depth ($\boldsymbol{D}$)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

Eq 18: Does it matter that the hole is full of water, in your LW calculations?

Although the model does not take into account the effect of water on the longwave radiation emitted from the CH wall, the effect on the simulation of the CH depth is probably little because the emissivity of the water is similar to that of the snow/ice surface (please see next our response to your comment).

L145: Why is the CH bottom temperature equal to the surface temperature? Shouldn't it simply be the melting point of ice? In cold conditions, under your assumption you would end up with the bottom of a water-filled hole cooling below 0C.

We have modified the explanation about the CH bottom temperature as suggested. In addition, Ti in Eqs (18) and (19) have been replaced with Tc.

Lines 154-159:

$$R_{Lw} = \cos^2\theta_c\,\varepsilon\sigma {T_c}^4. \tag{18}$$

Here, we assume that the CH wall or bottom temperatures (T_c) are equal to the melting point. Since the CryHo does not calculate water level in the CH, the longwave radiation emitted from the CH wall is calculated using the emissivity of the snow/ice surface, which is similar to the emissivity of the water, in the Eq. (18). Regarding longwave radiation emitted from the CH bottom, the net longwave radiation (R_{Lnc}; W m^{-2}) can be summarised as follows:

$$R_{Lnc} = R_{Lc} + R_{Lw} - \varepsilon\sigma {T_c}^4 = (1 - \cos^2\theta_c)R_{Lni}. \tag{19}$$

Section 2.4: I would encourage the authors to consider in more detail the influence of partial shading as I noted earlier, and also the change in zenith angle as the radiation enters the water.

As our response to your major comments 1 and 2, we additionally conducted the sensitivity test to assess the sensitivity of the CH depth to the solar zenith angle (θ_z-exp). Please see the major comments (1) and (2).

Also, does the transmittance through ice account for the low-density weathering crust? Maybe it doesn't matter for the deeper holes that are well below it, but something to consider in CryHo V2…

Previous study suggests that the density of the weathering crust is lower sometimes below 500 kg m^{-3} (Müller and Keeler, 1969). Because the transmittance of the downward shortwave radiation would be larger in such low-density case than in ice density case (900 kg m^{-3}), the CHs under the weathering crust may also develop. We have described the future challenges in Section 5.2.

Reference:

Müller, F. and Keeler, M.: Errors in Short-Term Ablation Measurements on Melting Ice Surfaces, J. Glaciol., 8, 91–105, https://doi.org/10.3189/S0022143000020785, 1969.

Lines 421:426:

Further studies on the optical characteristics of ice are necessary, because there is little information on the broadband flux extinction coefficients. Furthermore, as reported previously, a porous ice layer known as weathering crust, commonly develops at the surface layer of glacial ice during summer (Irvine-Fynn and Edwards, 2014; Stevens et al., 2022). The density of the weathering crust is lower sometimes below 500 kg m^{-3} (Müller and Keeler, 1969). Because the transmittance of the shortwave radiation would be larger in such a low-density case than in the ice density case assumed in this study (900 kg m^{-3}), the CHs under the weathering crust may also develop. In order to accurately simulate temporal change in CH depth, such weathering crust layer should be considered for the CH modeling in the future.

Section 3.3: I am quite untrusting of ablation measurements made using metal stakes, as they tend to melt into the ice unless they are installed deeply enough to be definitely remain well frozen at the bottom – could you comment further, or note it as a possible source of error (I think plastic tubes are better, but I acknowledge that opinions vary!)

In the observation, we buried the metal angle to the 1.5 m depth in the ice body for stabilization of the posture. The explanation has been added. (Lines 263-265)

Lines 263-265:

To collect in situ data that can be used for the evaluation of CryHo, the temporal changes in CH depth were observed using the monitoring device, which consisted of two time-lapse cameras as well as a plastic stick positioned in the centre of a CH, supported by metal angles buried to approximately 1.5 m depth in the ice body (Fig. 6a).

L296: A climate model can be used directly as a boundary condition rather than requiring any coupling, this is one of the great applications I can see for CryHo.

Thanks. We have a plan to do so.

L298: I didn't follow that sentence.

The sentence has been revised to clarify the content. (Lines 355-357)

Lines 355-357:

The sensitivity experiment regarding the shortwave radiation components (R_S-exp) suggests that

CHs tend to decay and develop in the case of that the direct and diffuse components are dominant, respectively (Fig. 9b). We then compared the contributions of each radiation component reaching the CH bottom during the experiment period (Fig. 10, red and blue lines).

L385: Conclusion that diffuse component dominates, may need to be revised depending on what you find if accounting for refraction or partial shading as noted above.

As our response to your major comment (1), the air-water refraction and partial shading hardly affect CH depths in the studied glacier suggested by θ_z-exp and θ_c-exp. In addition, Rs-exp suggests that CHs tend to decay and develop in the case of that the direct and diffuse components are dominant, respectively. Furthermore, heat component analysis suggests that CH depth is governed by the balance between the intensity of the diffused component of downward shortwave radiation and the turbulent heat transfer. Based on these results, we have kept the conclusion described in the line 385.

Table 1: great if the symbols are listed alphabetically.

We have listed alphabetically each symbol shown in Table 1.

Fig 5: you have plotted a single model run based on some estimated parameters. Could you use several runs, covering a range of plausible parameters, and plot the range or stdev of resulting hole depths as a shaded band? It would help interpret the discrepancy between model and obs.

We additionally conducted model simulations using different parameters of ice surface albedo and plotted the results (Figures 7 and 8 in the revised manuscript). The parameters are based on the standard deviation of the ice surface reflectance shown in Table 2.

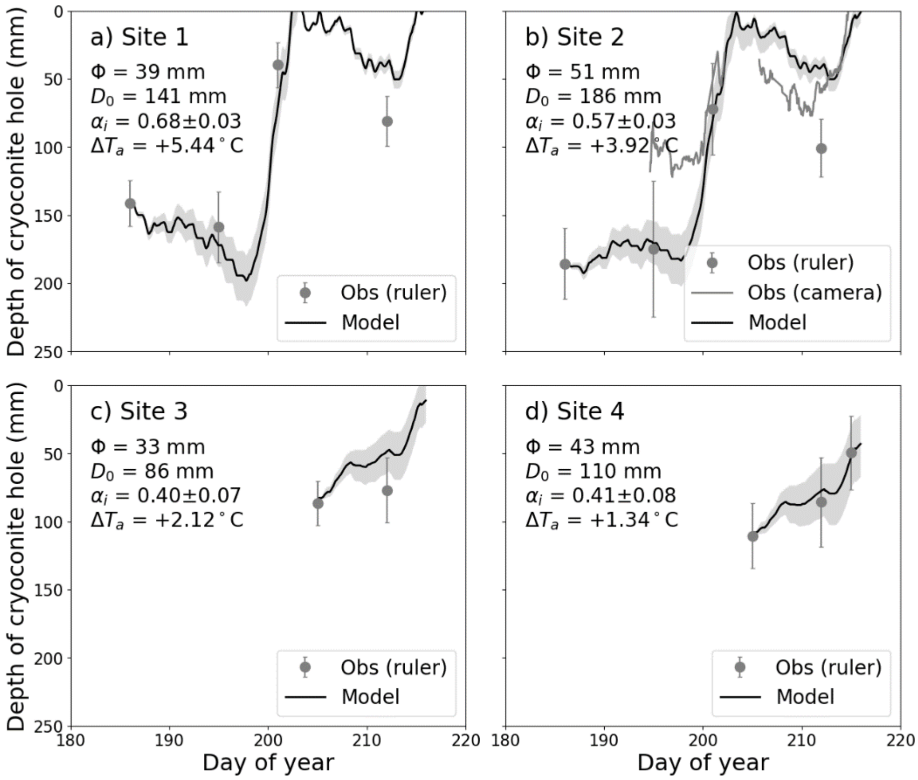

Figure 7: Temporal changes in cryoconite hole (CH) depth at (a) Site 1, (b) Site 2, (c) Site 3, and (d) Site 4 in 2014. The CH constants, ice surface albedo and air temperature correction are described in each panel. The black solid line and shading indicate model results using the average values and standard deviations of ice surface reflectance, which is assumed to be $\boldsymbol{\alpha_i}$, shown in Table 2. The missing grey solid line in panel b denotes the CH collapse period.

Supplement: It would be great if this could be avoided completely. Figs S1-S4 could be combined as a multipart fig in the main text. The text on extinction coeffs could also be moved to the main text, it's an interesting part of the model. Fig S5 can join Fig 3.
The supplemental text on the extinction coefficient has been moved to Section 2.4. Figures S1 and S4 have been moved to the main text because these figures are especially important to parameterize the extinction coefficient (Figures 2 and 3 in the revised manuscript). Figure S5 was merged with Figure 3 (Figure 5 in the revised manuscript).

Fig S6 (move to main text), can the individual Rs components also be plotted separately?
Figure S6 has been moved to the main text (Figure 10 in the revised manuscript). The five plots cover all patterns of the radiation components (all, direct, diffuse, transmitted, and hole mouth components), so we don't think it is necessary to further refine the information. Instead of that, we have modified the labels in the figure legend to clarify each plot (you can see Figure 10 in our response to your major

comment (1)).