Interactive comment on "Sensitivity of subglacial drainage to water supply distribution at the Kongsfjord basin, Svalbard"

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The Cryosphere Discuss., https://doi.org/10.5194/tc-2020-319, 2020

Authors' response to Christine Dow, Referee #2

We thank Christine Dow for her thorough and helpful review. We addressed her comments (shown in bold) point by point. Please also note the figure at the end of the document.

Main points

(1) I do, unfortunately, have a major concern, which is that the subglacial water pressure is far too low. It drops down to almost 0% of overburden during winter which is very unrealistic and then in the summer the mean pressure is less than 80%. From Figure 8, it looks like only a very small region of your domain gets to overburden pressure with the rest significantly lower. As a reference, boreholes that hit efficient systems often have pressure varying 20-60% overburden and that is considered low pressure. The distributed system should have high pressure, which would be anything above about 80% overburden. The reason that you have the seasonal and channelization behaviour that you see is that the model is spending most of the season building up to a background level of pressurization, which you would normally assume it would already have at the beginning of the season. Instead, with the spring event, water inputs should be into a system already close to overburden pressure. The rapid ice acceleration during this time is because often the basal system will increase to pressures above overburden, hydraulically jacking up the ice and allowing fast flow. I notice that you don't note in the manuscript how you spin up the model. For GlaDS (and many other models), you have to have a spin-up period so that the system can adjust to the background inputs, which in this case should be whatever basal water is available. You then have to make sure your chosen parameters allow as realistic a system as possible for when you initiate you seasonal inputs. This is why sensitivity tests are often used to assess the variations that parameters will have on the system and, with GlaDS, the two most important parameters to test are the sheet and channel conductivities. Set either too high and the system won't pressurize and is unrealistic. Set either too low and the model will break because the system will become too pressurized. From those sensitivity tests you then have a range of applicable conductivity values to use as a starting off point for your four experiments. If you have a look at the GlaDS literature for the Antarctic (Dow et al, 2018; Dow et al, 2020) and from Greenland (Poinar et al, 2019; Cook et al, 2020), you'll see that the sheet and channels conductivity values used are much lower (<1e-4 and <0.1, respectively) than have been applied in your study, which explains the low pressures throughout your domain.

Response: The reviewer raised concerns about unrealistically low water pressures before the onset of melting in our simulations, and further suggested that this behaviour was controlled by a too high hydraulic conductivity attributed to the sheet in our simulations.

Our value for the sheet conductivity (ks) is lower than the one originally proposed by Werder et al. (2013), but inspection of current literature revealed that others find better agreement to observations by using lower values (e.g. Dow et al., 2020) or even suggest a seasonally variable conductivity (Downs et al., 2018). Werder et al. (2013) simulated a single melt season and hence they did not experience the sheet running dry over winter (although they discuss this shortcoming), whereas multi-year simulations by the other studies explicitly address this problem. We agree with the reviewer that either too high or too low values for the sheet conductivity (ks) may thus lead to unrealistic results. However, we would like to emphasize that the aim of our study is to investigate the effect of different input configurations during the melt season rather than to obtain most realistic winter pressures.

Nevertheless, to test whether our results would be affected by adopting different values for ks and kc, we conducted sensitivity tests over the first three years of our 15-year long simulations. Whereas the overall results are largely insensitive to the choice of kc within reasonable limits (ks/kc ratio > $1.0e^{-2}$, with ks = [$1.0e^{-3}$; $1.0e^{-4}$] $m^{7/4}$ $kg^{-1/2}$ and kc = [$1.0e^{-1}$; $1.0e^{-2}$] $m^{3/2}$ $kg^{-1/2}$), lowering ks results in higher mean water pressures (above 50% of overburden pressure) throughout winter (Fig. S1), as well as in a more developed channel network (longer channels and higher connectivity) during the melt season. However, lowering ks also leads to substantially higher mean water pressures (above 60% of overburden pressure) during the entire melt season (Fig. S1), suggesting that the channelized drainage system indeed lacks efficiency and can only exist at high water pressure. While this increases the realism of our simulations, we also find that our original conclusions about limited influence of channelization and anti-clockwise pressure-input—hysteresis are robust, and hence are also the conclusions about the role of different recharge configurations.

We are now running the full 15-year simulations for all four experiments with a sheet conductivity (ks) of $1.0e^{-4}$ $m^{7/4}$ $kg^{-1/2}$, which yields more realistic winter water pressures, and we will update our results with these model outputs.

Regarding the spin up period, in our original simulations presented in the manuscript, the spin up period was very short, that is, after only a few days into the simulation water pressures were similar to water pressures of the following winter seasons (close to 0% of overburden pressure). This is why we included the spin up period in our analysis. However, in our new simulations with ks = $1.0e^{-4}$ $m^{7/4}$ $kg^{-1/2}$, the spin up period is longer as the wintertime water pressures of the first year are significantly lower than those of the next winter seasons. Therefore, in the revised analysis of our results, we will disregard the first year of the 15 simulation years in order to have a one-year spin up period.

(2) GlaDS also tends to have some issues with over-winter pressures if a spatially and temporally uniform basal sliding speed is used. This is because the basal sliding is applied in the cavity opening term. I would recommend taking the basal sliding rate as a percentage of the surface sliding rate to get the spatial variability, and then adjust this temporally using records of summer vs. winter velocity (if you have them). The latter doesn't have to be high temporal resolution but a lower sliding speed in winter causing less cavity opening will allow the system to repressurise (that's assuming that winter sliding speeds are lower than in the spring).

Response: Our sensitivity tests showed that adopting a lower value for the sheet conductivity (ks) allowed higher water pressures in the winter, so we consider this issue fixed. Again, we would like to emphasize that the focus of this study is on the effects of meltwater input configurations rather than on reproducing subglacial hydrological conditions outside the melt season.

Moreover, the glaciers of the Kongsfjord basin are, to some extent, likely soft-bedded and thus it is unlikely that feedback mechanisms between basal sliding and cavity opening dominate the overall drainage system at these glaciers, since cavities require hard bed conditions to open. The existence of a feedback mechanism between sliding speed and drainage efficiency for this kind of glaciers may not be adequately represented in GlaDS. This is why we chose to avoid introducing any additional complexity that may not be relevant in our case.

(3) My final main point is that, on the assumption you have access to ice surface velocities for the region, that is the best way to test whether the model is correctly representing your study region. Even a spatially averaged mean velocity should generally match the mean water pressure records that you show in Figure 3b. If these have the same pattern it would make your arguments about the subglacial system evolution stronger.

Response: In the revised version of the manuscript, we now qualitatively discuss how the surface velocity fields estimated in Schellenberger et al. (2015) compare with our modelled water pressure. While the fast-flowing outlets Kongsbreen North and Kronebreen coincide with modelled high water pressures, high water pressures in upstream regions (towards Isachsenfonna and Holtedahlfonna) do not correspond to higher surface velocities. This does not necessarily contradict our results since these regions are flat with very low driving stress that would lead to low surface velocity even for higher water pressures. Instead, this emphasizes that direct comparison between surface velocity and water pressure is not always relevant since ice flow also depends on glacier geometry. Validation of our results using velocity measurements would thus require an ice flow model, which is beyond the scope of our study.

Specific comments

Line 61) Why would the hydraulic potential minimum seed channels normally?

Response: By this sentence, we meant that simple theories for determining channel flow path are based on estimating the minimum hydraulic potential pathway. When surface meltwater is provided uniformly to the bed, channels will preferentially form along this pathway concentrating the water discharge, whereas local input from moulins is able to create channels anywhere by arbitrarily concentrating water flux. We clarified this part in the revised manuscript.

Line 157) "which participated". Also what do you mean by distributed model in this sentence?

Response: Fixed. Also "distributed" was changed to "two-dimensional".

Line 178) When you say HP 'set to zero' how do you apply that? As tidewater glaciers the outlet boundary condition would be best set at overburden but it's not clear if you do this.

Response: We actually do set the hydraulic potential at overburden. This boundary condition allows imposing water pressure to be equal to sea pressure at the depth of the outlet. Indeed, at the outlets we have

$$\varphi = \varphi_m + p_w = \rho_w g z_b + \rho_w g (z_{sl} - z_b) = 0$$

where φ is the hydraulic potential, φ_m the elevation potential, p_w the sea water pressure, z_b the bed elevation, and z_{sl} the sea level elevation (= 0 m a.s.l.).

Lines 197 and 373) Need some references for this statement. Most recent subglacial hydrology studies do use moulin inputs.

Response: "This approximation is most commonly made" was changed to "This approximation is still commonly made". References were added (e.g. Cook et al., 2020).

Line 206) Why only keep 10? How does this turn into 13?

Response: That sentence was indeed a bit confusing, therefore we changed it to “The other eight moulins were manually detected on high-resolution aerial images derived from TopoSvalbard (https://toposvalbard.npolar.no/, Norwegian Polar Institute).”

Line 265) It would be useful to know what that input is in m3/s in addition to the cumulative input for the total catchment that you state.

Response: We added this value in the revised manuscript.

Line 270) Why are the moulins only higher up (I may have missed this)?

Response: In contrast to Experiment 2, in Experiment 3 moulins only receive meltwater that is produced in their upstream watersheds. Therefore, the meltwater that is produced downstream of moulins is not taken into account in Experiment 3. Except for Kongsvegen, we did not detect any moulins in the lower parts of the other Kongsfjorden glaciers as these areas are highly crevassed. Meltwater input through crevasses is only accounted for in Experiment 4. We clarified this in the revised manuscript.

Line 289) State what output result it supports rather than what figure.

Response: “This figure supports Fig. 3(b) and Fig. 4” was changed to “This figure supports model results for basal water pressure (Fig. 3(b) and Fig. 4)”.

Line 314) What kind of numerical artefacts? Why would these occur?

Response: Short channel segments sometimes display instable behaviour and grow unrealistically large. Since GlaDS is built under the assumption of water-saturated channels, these local instabilities produce locally high discharge due to unrealistic channel radius. We clarified this in the revised manuscript.

Data availability – model outputs not provided.

Response: The underlying model outputs for all the figures presented in this paper will be deposited in a common public data repository after the manuscript has been revised.

Figure 1 – more detail needed for your below-sea-level elevations in panel b).

Response: Panel (b) was changed to add more detail to the below-sea level elevations, and colour of the line annotations was changed to improve the readability of the map.

Figure 2 – you have a lot of moulins on boundary points. That might cause problems if you reduce the conductivity to get the system closer to overburden.

Response: We did not encounter any problems in our sensitivity test runs.

Table 1 – basal sliding speed would be better stated in m a-1 and match what you say in the text.

Response: We kept the basal sliding speed stated in m s^{-1} in the table to keep consistency with the input to the model, but added the value in m s^{-1} in the text.

References

Response: The references mentioned by the reviewer will be added to the manuscript.

Cook, S. J., Christoffersen, P., Todd, J., Slater, D., & Chauché, N. (2020). Coupled modelling of subglacial hydrology and calving-front melting at Store Glacier, West Greenland. *The Cryosphere*, *14*(3), 905-924.

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Downs, J. Z., Johnson, J. V., Harper, J. T., Meierbachtol, T., & Werder, M. A. (2018). Dynamic hydraulic conductivity reconciles mismatch between modeled and observed winter subglacial water pressure. *Journal of Geophysical Research: Earth Surface*, *123*(4), 818-836.

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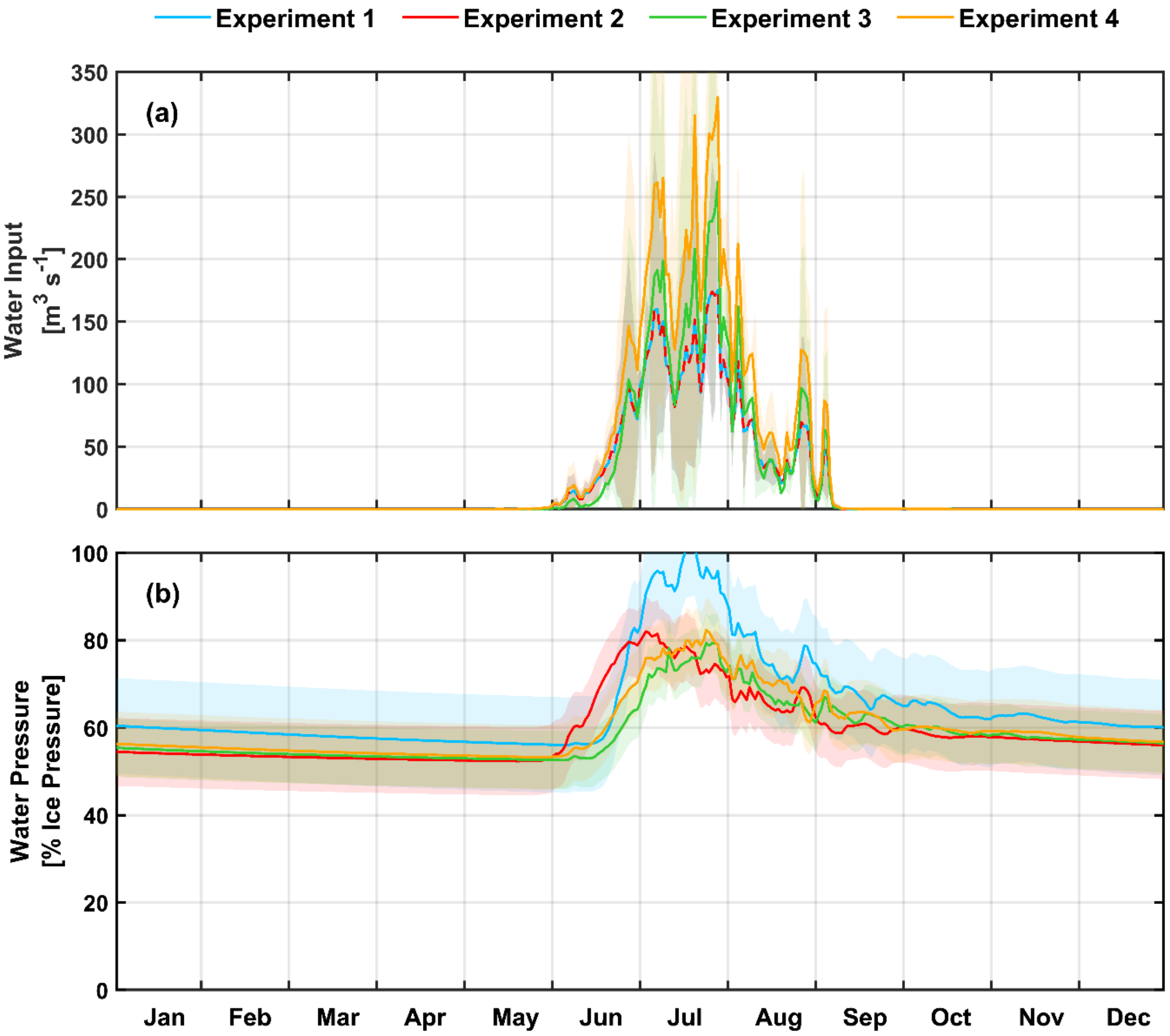

Figure S1. Mean (2004–2005) annual **(a)** water input and **(b)** basal water pressure averaged over the whole model domain for each experiment. The shaded area is the standard deviation showing the interannual variability of water input and water pressure for each experiment. Based on Figure 3 from the manuscript.