Review to 'Thermal regime of the Grigoriev ice cap and the Sary-Tor glacier in the Inner Tien Shan, Kyrgyzstan'

General comments

The authors apply 3D higher-order thermomechanical ice flow model to describe the thermal regime of Grigoriev ice cap and Sary-Tor glacier both located in the Inner Tien Shan. Historical air temperature and precipitation data, surface elevation and ice thickness measurements as well as the output of a surface energy mass balance model are used to constrain the thermomechanical ice flow model. The modelling results indicate cold conditions for Grigoriev ice cap and a polythermal structure for Sary-Tor glacier. These results agree with previous studies. The thermomechanical ice flow model indicates that the differences in thermal regimes are caused by higher ice velocities (higher horizontal advection rates), larger amounts of insulating snow and higher latent heat release on Sary-Tor. Furthermore, the authors present a sensitivity experiment which highlights that the thermal structure of the ice masses is not constant over time.

These are interesting and important results for a rather poorly studied region where only little knowledge exist about the thermal regime of glaciers. While the purpose of this study is clear and the general approach provides meaningful and relevant results, the clarity of the manuscript should be improved. I have a few general questions, which may point on such ambiguities, and also some general suggestions potentially contributing to the clarity.

In the introduction chapter more context would be helpful. I suggest to provide an overview of previous applications of 3D higher-order thermomechanical ice flow models to determine the thermal regimes of mountain glaciers. Ideally, applications of such models for glaciers with similar conditions (i.e. polythermal glaciers) and related limitations (and solutions) are introduced. This would help to convince the reader that the chosen method is suitable. Have this or similar models been applied to glaciers in the region before? Furthermore, the description of glacier thermal regimes should be improved. I suggest to follow the definitions in the Russian speaking literature based on Shumskii (1964), which is differentiated and therefore suitable for mountain glaciers. Later works by Kotlyakov (1984) and Krenke (1982) may also be worth to be considered here.

Regarding the method applied, I have some questions regarding the chosen boundary conditions. I furthermore suggest to include a quantification of uncertainties related to these choices.

Lower boundary conditions: As visible from figure 11, there is quite a misfit between modelled and measured temperatures at depth. How sensitive are these results to the lower boundary conditions? Have other values be tested? It would be good to expand the discussion regarding this and to visualize results of a related sensitivity experiment.

Upper boundary conditions: I wonder whether warming by latent heat release is correctly represented, especially for Sary Tor uncertainties might be quite high. Regarding the importance of r_{rem} together with w_f (and also s_{max} together with i_s), there estimation should be more thoroughly described and related uncertainties should be quantified. r_{rem} is quantified using a simple parametrisation of refreezing (within a mass balance model) which is a function of height and melt only. The model does thus not include any snow and firn characteristics (which are temporally and spatially heterogenous and have a major impact on refreezing), nor calculate internal accumulation. I suggest to expand the section about the mass balance model describing how r_{rem} is estimated. It would be interesting to do simulations for different r_{rem} values in order to quantify related uncertainties. If I understand correctly, potential errors in r_{rem} may be corrected for by tuning w_f to subsurface temperatures on Grigoriev ice cap and furthermore may be averaged out by using

averages over several decades. The uncertainties might thus be reduced if calibration data is available. This could be discussed together with quantification of the sensitivity regarding r_{rem} and comparison to literature values of r_{rem}. Potentially, different r_{rem} values could also be discussed in the context of climate change and changing glacier zones (zones by Shumskii, 1964) see my comment above). This would help to interpret the results for Sary Tor, where firn conditions (and refreezing) are likely different (due to different firn conditions related to higher precipitation rates) and for potential other sites, where no calibration data is available.

Besides this, the methodological description would become clearer if somewhat restructured. It is a bit confusing that both chapter 2 and 3 present data descriptions. Chapter 2 seems to mainly refer to historical data. I suggest to either (i) rename chapter 2 to "Study area" and 2.2. to "Historical englacial temperature measurements" or to (ii) move all the data descriptions to chapter 2. Chapter 3 could be a bit better structured by separating background information (which could be moved to the introduction), model description, and data used (or move this to chapter 2) more clearly. The description of the mass balance model deserves more details (parametrisations). When restructuring, the length of subchapters which sometimes seem a bit arbitrarily chosen should be homogenized and the headings could be optimised.

The results chapter presents relevant results and also contains elements of a discussion. Please rename the chapter results and discussion or even better strictly separate results and discussion. The discussion should be a bit more complete. Please also revise whether 4.1. really belongs to the results. It might also be moved to the method chapter, where a section about calibration could be added.

The discussion in chapter 5 could be extended (see also my comments above on the boundary conditions). Furthermore, the uncertainties of the study could be contextualised by referring to previous studies. In section 5.2., I think it would be interesting to discuss a potential firn warning on Grigoriev (as a response to different parameter disturbances) than just saying that the site remains cold. The statement from the abstract 'a detailed analysis concerning the influence of temperature and precipitation changes at the surface reveals that the thermal structure of both ice bodies is not a constant over time, with recent climate change causing more temperate ice in higher areas' could be underlined more with the discussion in 5.2.

In addition to these remarks, I have some more specific and technical comments.

Specific comments

L8/9 delete the first sentence of the abstract and complete the second: "An accurate knowledge of the thermal regime of glaciers and ice caps is important to understand their dynamic and response to climate change, and to model their evolution."

L17-19 statement needs to be corrected/rephrased. Not sure, whether the term superimposed ice is correct here. I expect latent heat release being relevant also from other processes than the formation of superimposed ice. Refreezing of melt water above and also below the last summer horizon (internal accumulation) are probably very important processes as described for Sary Tor in Dyurgerov & Mikhalenko (1995) and also described in Kronenberg et al. (2016)and indicated by ice lenses and layers in Grigoriev cores (e.g. Takeuchi et al., 2014; Thompson et al., 1997).

L19 The use of the term 'ice surface temperature' might be confusing, see also later comment.

L30-32 Please be a bit more specific here. I suggest to add one or two sentences + references why such knowledge is needed and how the thermal regime affects the response of ice bodies to climate change.

L38&L41 As Abramov glacier is located in the Pamir Alay and not in the Tien Shan, I am not sure whether it should be mentioned here. If so, I suggest to write something like 'Abramov glacier located in the nearby Pamir Alay and rather refer to the subsurface temperature measurements directly (Kislov et al., 1977), which indicated cold temperatures in the ablation area and temperate conditions in the accumulation area. Please also note, that in the uppermost meters, seasonal cooling is quite substantial on Abramov glacier, but all the cold content in the accumulation area is 'consumed' by refreezing of melt water leading to temperate conditions (cf. Kronenberg et al., 2022).

L51-54 Please verify statements and cited references here. At least Kronenberg et al. (2021) does not state this. In the infiltration-congelation zone, the refreezing of melt water is limited by the amount of available pore space and not by temperatures which are rather cold (than temperate) here (Shumskii, 1964).

L54-56 statement unclear. Do you refer to the infiltration zone as defined in Kotlyakov, (1984); Krenke (1982)? What is thawed melt-water? Depending on the site, infiltration-congelation zone is the lower-most zone (cf. Shumskii, 1964).

L80 calving → dry calving

L86 delete 'on the other hand'

L86 what is small? Better provide area in km^2

L106-114 this rather belongs to the introduction than to the data section. Also, it seems that some statements are repeated from above

L114 reference needed

L120 warm →temperate

L135 last → deep

L135 on the top →near to the summit

L142 delete last statement

L151 what kind of mountain glaciers? What climatic environment? Maybe also provide this information in the introduction…

L151-153 was there a study using the same model and providing a detailed description? Would be good to state here, which study this was and write something like: "In the following the model is briefly described. Please refer to xx and references therein for a more detailed description. "Despite this, make sure that the reader knows the basis of your choices such as chosen parameters etc.

L164 why 3? Reference

L164 and also elsewhere always write (eq. 2) and not just (2) when referring to equations

L167 I am not sure whether this should be written here or whether there might a better place to describe the spatial resolution. Might also be good to recall what the average layer thickness is (for both sites)

L175 provide reference

L202 provide typical values of m for typical conditions…

L235 (Barandun et al., 2015) is in the Pamir Alay. I don't know whether this is relevant here.

L249-251 verify statement/definition of the zone (see also previous comments)

L256 Here and probably also later, it might be clarifying to write 'surface layer' instead of 'surface' e.g. "…meltwater refreezing and its warming effect on the glacier surface layer"

L266 Rather provide an example from a glacier or better introduce this, otherwise the reader is very surprised that you start to talk about permafrost here..)

L276-280 Make sure, that this paragraph really states what you would like to, what is not fully clear as it is written now).

L285 'for all the effects described above' is unclear

L290 why sinusoidal and not monthly lapse rates provided by (Aizen et al., 1995)

L293 refer to section describing mass balance model (in more detail than it is currently done).

L297 It would be good to justify this choice, as most precipitation is falling during summer months cf.(Dyurgerov et al., 1994; Kronenberg et al., 2016)

L342-343: Why does the water refreeze at the end of the mass balance year? What are the implications of this assumption and of the assumption of the chosen threshold of 60 %? How does this estimation compare to more sophisticated simulations of refreezing? And what is about refreezing below the last summer surface?

L347-348: Can this choice be underlined by in situ measurements? (See also comment above. To my knowledge, most precipitation is falling during summer months and I would therefore assume substantial snow mass being accumulated after May.)

L375: Can you please quantify the uncertainties of this assumption? Why not use a DEM based on optical data?

Section 3.5.4: I suggest to delete this section and to add the relevant information to section where you describe the outlines.

L421 15% larger than what?

L422 ~30% more than what?

L423 The values given for Sary Tor here are different from the ones given above. Is this due to your correction based on melt? I don't fully understand this correction and it is difficult to get, why the values are presented once more.

L426 refer to a map which shows this eastern tributary

L438-443 These are not results. Also, Grigoriev ice cap is strongly wind-exposed and wind erosion may also play a major role here.

L450/451 It is not very clear here, where these values are coming from. Are they optimised to obtain a better fit between the measured and modelled glacier extent for 1990. (I assume so from the statement in L397). This somehow implies that the mass balance model does not provide suitable mass balance estimates. Does this not also question the mass balance model estimates of the refreezing?

L466 please provide units. And maybe recall, what w_f stands for (firn warming parameter).

L466ff this is rather a discussion than results.

L467 I doubt that this is a valid argument here. Refreezing won't take part at depth, but only in the firn. Furthermore, refreezing may be reduced due impermeable ice layers cf. (Machguth et al., 2016)

L472 please provide units.

L482 I think this is rather related to the lack of firn pore space than due to a thin snow pack. The firn is likely thinner and with higher densities in the lower accumulation area.

L486 Summer precipitation is also mostly snow (cf. e.g. Dyurgerov et al., 1994, Kronenberg 2016).

L488 surface →surface conditions (2x)

L493 ensures a larger cooling of the surface → allows for a larger surface cooling

L512 'The enhancement factor is set at 3 for the Grigoriev ice cap and at 4 for the Sary-Tor glacier, which appears to be the optimal value to match with the reconstructed ice thickness of 1990.' Is not really a result. I suggest to rather provide this information within the method chapter adding a section where you describe the calibration.

L515-522 Please shorten this paragraph saying the modelled and reconstructed topographies match well and discrepancies are mainly occurring in areas where no GPR measurements exist.

L525 How do your measurements of the ice thickness compare to the deep core which was drilled relatively near to the summit (Takeuchi et al., 2014)

L527 Please provide a refence for the statement about the complexity of modelling ice thicknesses at ice divides

L529 Please provide a reference for the enhancement factor of 1 corresponding to -5°C (rather write °C than 'degrees').

L542 Please refer to the map in fig 8c it here.

L561 Please add here, when these observations were performed.

L572 Please use full variable names and give short forms in brackets.

L573: Should an improved transport of geothermal heat not rather lead to a warming?

L576 ensures →shows?

L579-580 Please rephrase 'This ensures a greater stiffness which causes the ice intrinsically slower to deform.'

L584/585 Not clear, why temperate ice causes the infiltration of water. Water can either infiltrate into ice through crevasses, moulins or infiltrate into the firn unless an impermeable ice layer is

reached within the firn (Machguth et al., 2016). Such infiltration occurs in cold and temperate firn (Shumskii, 1964).

L587 'This is the case for the entire surface of the Grigoriev ice cap'. This is not correct. Water percolation of into the subsurface also occurs on Grigoriev as e.g. visible from ice lenses within the firn in different cores from (Takeuchi et al., 2014; Thompson et al., 1997)

L613/614 This statement needs a reference. And, also, it is not fully clear why this is written here. I suggest to rephrase the paragraph so that the argumentation becomes clearer.

L627 Where do the mean climatic conditions for 1920-1950 come from? Does the Kumtor time series not start in the 1930s?

L630 Could the mismatch in fig. 11 between simulations and measurements not also be (partly) related to a wrong lower boundary condition and/or the used temperature gradient? Would be interesting to visualize of the corresponding sensitivity experiment here.

L675 the way, how w_f and especially i_s are calculated also has uncertainties. This should be discussed here, as the overall temperature regime seems to be very sensitive to i_s

L705 From Figure 12 it seems, that warming temperatures cause an increase of the percentage of temperate ice on Grigoriev. So, the statement that it remains cold should be corrected. Also, do your simulation show a warming happening with warmer temperatures. Even if temperatures stay below the melting point, a warming may be happening – would be interesting to briefly discuss this here and maybe put into context with observed and modelled firn warning in the alps (Hoelzle et al., 2011; Mattea et al., 2021; Vincent et al., 2020)

L717 not only the formation of superimposed ice (which happens at the edge of the accumulation area) releases heat, but also refreezing of melt water within the firn is a relevant warming process.

L718 Please change 'This has already been observed at the Abramov glacier in the southwestern Tien Shan (Kronenberg et al., 2020).to 'Evidence of a precipitation increase has been observed on Abramov glacier in the Pamir Alay (Kronenberg et al., 2021)'

L735 'reduced formation of refrozen meltwater at the end of summer' → 'reduced refreezing of melt water' (Refreezing is an ongoing process, not restricted to the end of summer. Especially on temperate sites, it happens at the beginning of the melt season (cf. Kronenberg et al., 2022)

L737 This may be the case in the model applied here, which does not account for firn. But is not true in general. Melt water is known to infiltrate to the subsurface also under cold conditions (Shumskii, 1964).Please clarify here.

L766 Sary-Tor →Grigoriev

L870 2020 →2021

Technical corrections

References: Please add references to statements where they are missing and make sure that all references are given following the journal's guidelines. Sometimes, the year is provided in brackets, sometimes not.

The language of manuscript could be improved I recommend a proofreading by a native speaker.

General comment on the tables: Please homogenize the table layout. I suggest to use a typical layout without coloured lines, shaded areas etc.

General comment on figures: Please add panel letters to all the figures which show more than one plot/map and refer to those letters in the captions. Use larger fonts in legends and labels. Plot legends aside and not on the top of maps/plots and show them in a reasonable size (they are small and difficult to read). Place labels on maps more carefully so that the they are better visible. Complete information in caption (year of glacier outlines is usually missing, say that the legend is for all the subplots etc.).

Table 2: provide units also in the table (and not only in the caption). Does 1986-1987 refer to the mass balance year starting from 1.10.1986 and ending on the 30.9.1987? If so rather write 1986/87. And replace 'Average 1963-1989' with 'average 1963/64-1988/89'. Provide reference in a sperate column. Also, it seems strange that the glacier wide value is given in the centre. Either provide it first or last. And 'at the front' is very unspecific. Due you refer to a point measurement here or to some averaged value? Please show on a map where this is and specify, whether always the location is used.

Figure 1: add legend with information about of background topography

Figure 3: Zoom in to Sary Tor. The glacier is quite small and you loose space by showing its surroundings. Visualize core locations on Grigoriev map.

Figure 5b display x and y axes with the same length.

Figure 6: Provide x/y axes for all panels or say in the captions that they stand for all. Improve legend!

Figure 8: If D in panel d corresponds to D in panel c, 'A' should be replaced with 'C' in panel c.

Figure 9: cross-reference in caption wrong (should be figure 8 or 7). Add letters: A,B,C,D

Figure 10 Clarify the colour bar. Is the darkest red colour tone in the left panel referring to temperatures at 0°C. What does the second class stand for? Values between -0.5 and -1°C? Plot the simulated boundary between temperate and cold ice in the right panel. And show both panels at equal spatial resolution

Figure 11: was the purple profile simulated by a stepwise temperature increase or was the change applied once?

Figure 12: homogenize font sizes of axes labels

References

Aizen, V. B., Aizen, E. M., & Melack, J. M. (1995). Climate, Snow Cover, Glaciers, and Runoff in the Tien Shan, Central Asia. *Water Ressources Bulletin*, *31*(6), 1113–1129. https://doi.org/10.1111/j.1752-1688.1995.tb03426.x

Barandun, M., Huss, M., Sold, L., Farinotti, D., Azisov, E., Salzmann, N., Usubaliev, R., Merkushkin, A., Hoelzle, M., A.Merkushkin, & Hoelzle, M. (2015). Re-analysis of seasonal mass balance at Abramov glacier 1968-2014. *Journal of Glaciology*, *61*(230), 1103–1117. https://doi.org/10.3189/2015JoG14J239

Dyurgerov, M. B., & Mikhalenko, V. N. (1995). *Glaciation of Tien Shan [in Russian]* (M. B. Dyurgerov & V. N. Mikhalenko, Eds.). VINITI.

Dyurgerov, M. B., Mikhalenko, V. N., Kunakhovitch, M. G., Ushurtsev, S. N., Chaohai, L., & Zichu, X. (1994). On the cause of glacier mass balance variations in the Tien Shan mountains. *GeoJournal*, *33*(2--3), 311–317.

Hoelzle, M., Darms, G., Lüthi, M. P., & Suter, S. (2011). Evidence of accelerated englacial warming in the Monte Rosa area, Switzerland/Italy. *The Cryosphere*, *5*, 231–243. https://doi.org/10.5194/tc-5-231-2011

Kislov, B. v, Nozdrukhin, V. K., & Pertziger, F. I. (1977). Temperature regime of the active layer of Abramov Glacier [in Russian]. *Materialy Glatsiologicheskih Issledovanii (Data of Glaciological Studies)*, *30*, 199–204.

Kotlyakov, V. M. (1984). *Glaciological Dictionary [in Russian]* (UDK 55.132, pp. 1–564). Gidrometeoizdat.

Krenke, A. N. (1982). *Mass exchange in glacier systems in the USSR [in Russian]*. Gidrometeoizdat.

Kronenberg, M., Barandun, M., Hoelzle, M., Huss, M., Farinotti, D., Azisov, E., Usubaliev, R., Gafurov, A., Petrakov, D., & Kääb, A. (2016). Mass-balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. *Annals of Glaciology*, *57*(71), 92–102. https://doi.org/10.3189/2016AoG71A032

Kronenberg, M., Machguth, H., Eichler, A., Schwikowski, M., & Hoelzle, M. (2021). Comparison of historical and recent accumulation rates on Abramov Glacier, Pamir Alay. *Journal of Glaciology*, *67*(262), 253–268. https://doi.org/10.1017/jog.2020.103

Kronenberg, M., Machguth, H., Pelt, W. van, Fiddes, J., Hoelzle, M., & Pertziger, F. (2022). Long-term mass balance and firn modelling for Abramov glacier, Pamir Alay. *The Cryosphere Discussions*, *2021–380*, 1–33. https://doi.org/10.5194/tc-2021-380

Machguth, H., MacFerrin, M., van As, D., Box, J. E., Charalampidis, C., Colgan, W., Fausto, R. S., Meijer, H. A. J., Mosley-Thompson, E., & van de Wal, R. S. W. (2016). Greenland meltwater storage in firn limited by near-surface ice formation. *Nature Climate Change*, *6*, 390–393. https://doi.org/10.1038/nclimate2899

Mattea, E., Machguth, H., Kronenberg, M., van Pelt, W., Bassi, M., & Hoelzle, M. (2021). Firn changes at Colle Gnifetti revealed with a high-resolution process-based physical model approach. *The Cryosphere*, *15*, 3181–3205. https://doi.org/https://doi.org/10.5194/tc-15-3181-2021

Shumskii, P. A. (1964). *Principles of structural glaciology*. Dover Publications Inc.

Takeuchi, N., Fujita, K., Aizen, V. B., Narama, C., Yokoyama, Y., Okamoto, S., Naoki, K., & Kubota, J. (2014). The disappearance of glaciers in the Tien Shan Mountains in Central Asia at the end of Pleistocene. *Quaternary Science Reviews*, *103*, 26–33. https://doi.org/10.1016/j.quascirev.2014.09.006

Thompson, L. G., Mikhalenko, V. N., Mosley-Thompson, E., Dyurgerov, M. B., Lin, P. N., Moskalevsky, M., Davis, M. E., Arkhipov, S., & Dai, J. (1997). Ice core records of recent climatic variability: Gregoriev and It-Tish ice caps, in central Tien Shan, Central Asia. *Materialy Glatsiologicheskih Issledovanii (Data of Glaciological Studies)*, *81*, 100–109.

Vincent, C., Gilbert, A., Jourdain, B., Piard, L., Ginot, P., Mikhalenko, V., Possenti, P., le Meur, E., Laarman, O., & Six, D. (2020). Strong changes in englacial temperatures despite insignificant changes in ice thickness at Dôme du Goûter glacier (Mont Blanc area). *The Cryosphere*, *14*, 925–934. https://doi.org/10.5194/tc-14-925-2020