Thank you for your detailed and helpful comments and suggestions. In the text below, reviewer comments are indicated with colored background, our replies are in plain text and our changes to the manuscript are put in italic.

Response to major comments

Major comment 1

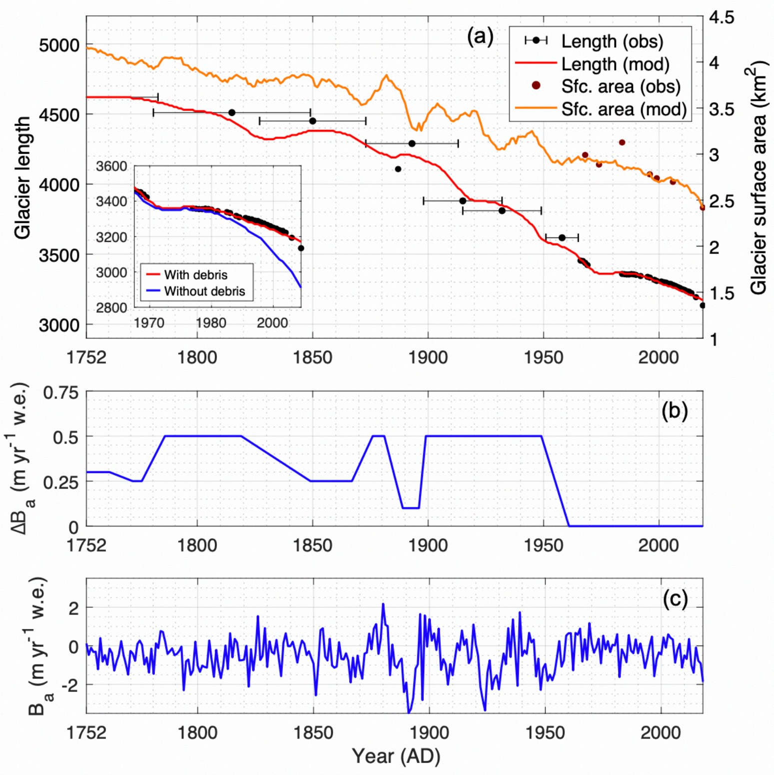
>> Evaluation of glacier change in terms of terminus position and glacier area: We know that debris-covered glaciers have a different response to climate warming based on remote sensing observations and numerical modelling, which shows that they lose the majority of mass by surface lowering rather than terminus recession. Therefore, the metrics that are useful for clean-ice glaciers are poor indicators of the behaviour of a debris-covered glacier. My main concern with the study is that the debris model is unnecessary given the characteristics of Djankaut Glacier (e.g. large areas of visible clean ice on the tongue, steep slope below the ELA, high velocities, large changes in length and area over several decades, short response time) and introduces a bias to the results. It would be valuable to demonstrate the difference between simulations with and without the debris-cover model to evaluate its impact on glacier change and if the observed change can be replicated without this additional calculation. It appears that the info is contained in Fig. 14, which shows future glacier evolution under different climatic forcings, but is not discussed in the text and the figure is difficult to interpret; it appears that the debris has no impact on glacier length change until the second half of the century.

Indeed, our experiments brought to light that an extensive debris cover on Djankuat Glacier is a more recent phenomenon, largely linked to glacier retreat exposing debris sources, however that was not made very explicit in the manuscript. On the other hand, debris cover becomes an important characteristic of the glacier in the future. In that sense, we disagree with the reviewer that the debris cover is unnecessary to study the future behavior of Djankuat Glacier. We have more explicitly addressed this issue by including the results of an additional experiment without debris cover. Both model runs with and without debris cover exhibit very similar results prior to the observational period. As shown in the new inset in Fig. 9 below, debris played only a minor role prior to ca. 1980 AD, with length differences of only 20 to 40 meter. By 2009/10 AD, however, the length difference between both runs is already modelled to be 160 meter. This is also evident from observations, where one can clearly see that the debris-free section of the snout has retreated faster than the debris-covered section. In the manuscript, the following additional explanation was therefore added (Line 409):

> *A historic model run conducted with a 100 % clean-ice glacier, shown as an inset in Fig. 9a, revealed that debris played only a minor role prior to ca. 1980 AD, with length differences of only 20 to 40 meter. By 2009/10 AD, however, the modelled length difference between a debris-free and debris-covered glacier already increased to 160 meter."*

And (Line 451):

> *"Despite present-day areas of visible clean ice on the tongue, a steep slope below the ELA, relatively high ice velocities, and a short response time, also observations show that the supraglacial debris cover on the Djankuat Glacier has significantly affected glacier geometry during the last several decades, as evident from the differential retreat of the snout (Fig. 1).*



Updated Figure 9. Historic variations of (a) the modelled and observed glacier length of the Djankuat Glacier since 1752/53 AD until 2017 AD, (b) additional mass balance perturbations ΔB_a and (c) reconstructed time series of the total annual mass balance Ba of the Djankuat Glacier with changing geometry. Observed length variations are derived from lichenometric dating of moraines in the valley, historic documents, and/or field measurements and/or recent satellite imagery (Boyarsky, 1978; Zolotarev, 1998; Petrakov et al., 2012; WGMS, 2018). An additional model run for a 100% clean ice glacier was conducted is shown in the inset in panel a.

We have furthermore expanded the discussion of Figure 14 to underline that supraglacial debris cover is of large importance for the future evolution of the glacier:

> *The figure shows the impact of debris input location x_{debris}, the time of release of the debris source from the surrounding topography t_{debris}, and debris flux magnitude F_{debris} (rows) on the future length extension of the Djankuat Glacier under different climatic scenarios (columns). The black lines indicate the scenario where no additional debris source is released in the future. The other lines are for experiments that include an additional future debris source from the surrounding topography for varying values of the earlier mentioned debris-related parameters. It is clear that the addition of an increasingly widespread debris cover dampens glacier retreat. It should be noted that the effects on glacier length are not immediate, as it takes some time for the debris to be advected to the terminus after its initiation at time t_{debris}.*

Major comment 2

>> Value of sub-debris melt calculation: In relation to my point above, I have two concerns about the debris-cover model; (a) the gradient of the exponential function used to scale sub-debris melt is steep using H*debris = 1.15 m (see review Fig. 1), and (b) the thickness of debris on the glacier is similar to the critical thickness observed on debris-covered glaciers elsewhere and therefore likely to both enhance and reduce ablation across the tongue. The glacier model accounts for the impact of supraglacial debris by reducing mass balance, a valid assumption beneath debris that is thicker than a critical thickness of about 0.1–0.2 m. An exponential function is used to reduce ablation with debris thickness. However, images of the present day glacier including Fig. 1 and data presented in the manuscript (Fig. 5a) illustrate that the debris thickness at the terminus is ~1.0 m in 2010 and was <0.5 m before 1990. As debris thickness decreases rapidly upglacier (Fig. 5c), is the same scaling is assumed then most of the debris layer was <0.25 m thick before 1990 and therefore close to the critical thickness. For such thin and discontinuous debris layers, there is likely to be little reduction in ablation due to insulation by the debris layer (the exponential function used here will only reduce sub-debris melt by <20% compared from the clean-ice value – see review Fig. 1) and instead an enhancement of ablation due to the reduction in albedo of debris-covered ice compared to clean-ice surfaces. The model does include an albedo term but does not use this to adjust for the impact of debris on ablation.

We understand the reviewers' concern related to the decay of the exponential curve for H*debris and acknowledge that the value found for Djankuat Glacier deviates somewhat compared to earlier research for other glaciers. As pointed out in Anderson and Anderson (2016) and Lambrecht et al. (2011), the value for H*debris depends, amongst other factors, on the thermal conductivity of the debris material, the debris cover porosity and is also influenced by the debris layer water saturation. Values for these factors seem somewhat out of range for the Djankuat Glacier and explain the deviating value of the H*debris parameter (Anderson and Anderson, 2016; Lambrecht et al., 2011; Bozhinskiy et al., 1986). The following section was added to the manuscript for clarification (Sect. 3.1, Line 262):

> *"A value of 1.15 meter was found for H*debris. The gradient of the exponential decay is somewhat out of range with respect to earlier studies for other glaciers (e.g. Anderson and Anderson, 2016). Explanations for this high value of H*debris can be found in the relatively high thermal conductivity of the granite-type debris cover on the glacier (2.8 W m^{-1} °C^{-1}) and the high debris cover porosity (0.43 in the case of Djankuat Glacier, Bozhinskiy et al., 1986). Also the relatively low water saturation, as mentioned by Lambrecht et al. (2011), suggests that heat conduction towards the debris-ice interface seems to occur quite easily on the Djankuat Glacier."*

With respect to the inclusion of the melt-enhancing effect for thin debris, studies performed on Djankuat Glacier point to a lower value of the critical thickness than mentioned by the reviewer (0.03 m by Lambrecht et al., 2011 and 0.07 m by Bozhinskiy et al., 1986). The areal fraction of debris cover on the Djankuat Glacier that holds such thin thickness values is very small, so we believe that the ablation enhancement effect of thin debris plays a very minor role on Djankuat Glacier. Therefore, this factor was not included in the parameterization. The following section was added to the revised manuscript for justification (Line 224):

> *"The melt enhancement that may occur for a very thin debris cover was not implemented. Values in the literature of the critical debris thickness for the Djankuat Glacier vary from 0.03 m (Lambrecht et al., 2011) to 0.07 m (Bozhinskiy et al., 1986). The areal fraction of Djankuat Glacier that holds these thin thickness values is very small (Popovnin et al., 2015) and are therefore not believed to have a significant influence on the ablation of Djankuat Glacier."*

The following limitations were furthermore added for completion, after Line 228:

> *"The debris model also neglects other processes that may potentially play a role in the spatial and temporal distribution of debris, such as the formation and thickening of medial moraines, ice cliffs and surface ponds (Anderson and Anderson, 2016)."*

Major comment 3

>> Evolution of the debris layer: As observed in Fig. 5, the debris layer has thickened by a factor of 2–3 over the last 20 years. Djankaut Glacier is steep, fast-flowing and thinly debris-covered over a section of its ablation area, and based on this geometry and the presence of large ice-marginal moraines it seems likely that during the LIA and subsequently, the glacier exported the majority of its debris to its margins rather than developing a supraglacial layer. Therefore, the assumption in the spin up simulation that the glacier is debris covered (Section 5.1) may not hold. However, from Fig. 14 it appears that the debris layer has no impact on glacier change until about 1970 CE.

We agree that the increasingly widespread supraglacial debris cover on Djankuat Glacier is a more recent phenomenon, largely related to exposure of debris sources due to glacier retreat and climate warming. We furthermore refer to the new Fig. 9a in general comment 1 to demonstrate that the debris cover only became important during the last several decades, and has had little influence prior to ca. 1980 AD. However, there is also an indirect evidence for the presence of at least some supraglacial debris in the historic period, shown by e.g. the presence of end moraines in the valley (Fig. 1), and a photograph taken around 1930 AD that shows some debris patches on the snout (Aleynikov et al., 2002). It is furthermore unclear to us how we could have initialized the glacier model at the LIA without debris cover. The following section was therefore added to the manuscript to discuss this issue (in Sect. 5.1):

> *"As can be deduced from the large lateral moraines in the Adylsu Valley (Fig. 1) and fast-flowing nature of the paleo-glacier tongue in the valley (up to 100 m yr^{-1} around 1752 AD, Fig. 6d), Djankuat Glacier used to export most of its debris to the margins rapidly in the historic period, rather than developing a supraglacial debris cover. Furthermore, debris sources from surrounding topography were likely less widespread in the historic period because the slopes were covered by the glacier itself and were more stable in a colder climate. For this reason, supraglacial debris is believed to have been much less widespread prior to the observational period of 1967/68 AD, implying that the glacier was not very much influenced by debris cover in the historic period. However, there is also indirect evidence for at least some supraglacial debris in the historic period from the presence of end moraines in the valley (Fig. 1) and a photograph taken around 1930 showing some debris patches on the snout (Aleynikov et al., 2002). It would be furthermore unrealistic to only introduce a debris cover in the model once the model approaches the start of the observations. This would contradict the presence of moraines and the observation that there already was an expanding debris cover during the first data collection in 1967/68 AD (Popovnin et al., 2015). Because there is no direct evidence for the origin of the debris cover, it was chosen to include melt-out processes in the model from the initialization onwards."*

As a minor point, Fig. 14 (now Fig. 12) only showed results after 2009, so we are a bit puzzled how reviewer 2 came to the conclusion that the debris layer has no impact until about 1970 CE.

Major comment 4

>> Lack of discussion: The manuscript organisation is somewhat unconventional. After the Introduction, Methods and Model Description, there are four Results sections (not named as such) followed by the Conclusions. There is very limited discussion of the context of results and their interpretation, and no dedicated section for this.

We organized the manuscript in such a way that discussion items are merged into the result sections, so that all information related to one specific subject appears sequentially in a chronological, continuous text. This way of structuring was preferred, rather than jumping from one section to another. However, also in response to the other reviewers, the discussion was expanded in several places. This included additional discussion on model validation versus model calibration, justification of assumptions in the debris cover model, and the effect of debris on future glacier evolution.

Response to minor comments

>> Line 13: "retreat" see major comment 1 about terminus recession versus surface lowering.

To elaborate more on the thinning out of debris-covered glaciers, we added (Line 51):

"If a thick supraglacial debris cover is present over a large portion of a glacier's ablation zone, surface melting and terminal retreat can be drastically suppressed, even under a warming climate (e.g. Scherler et al., 2011; Benn et al., 2012). In such cases, debris-covered glaciers are shown to lose mass by lowering the surface in their ablation zone (downwasting), rather than by terminus retreat (e.g. Hambrey et al., 2008; Rowan et al., 2015)."

>> Line 15-16: The change in glacier length and area stated here are not meaningful unless the initial length and area are also given, or these are stated as % change.

Done. This was rectified in the text:

"… have decreased by 1.4 km (- 29.5 %) and 1.6 km² (-35.2 %) respectively…"

>> Line 24-25: Vague statement.

We have included some references to these sentences:

"… changing climate (e.g. Shannon et al., 2019; Zekollari et al., 2019; Hock et al., 2019)."

>> Line 39: Use of "significantly" should be reserved to its precise statistical meaning, whereas here it is used for emphasis and could be replaced with "dramatically" or in this sentence the meaning would be the same if this word was removed.

The word 'significantly' was removed and replaced by 'drastically'.

>> Line 45-47: What is the glacierised area and debris-covered area in the Caucasus in km2? This is needed to indicate the context suggested in this statement.

The total glaciated area is stated in Line 30 (691.5 ± 29.0 km² in 1986, 590.0 ± 25.8 km² in 2014). The manuscript mentioned on Line 46 that 26.2% of that glacierized area is debris covered, referring to Scherler et al. (2018). Hence, the debris-covered area is ca. 155 ± 6.7 km² for present-day conditions. This number is now added:

"…be 26.2 % at for present-day conditions (ca. 155 ± 6.7 km²), hence enabling…"

>> Line 53: Citations to previous modelling studies of debris-covered glaciers. Please note that Rowan et al. (2015) did not use a simple parameterisation of the impact of debris on mass balance as stated here, but instead made a dynamic simulation of the feedbacks between ice flow, debris transport and mass balance using a higher-order ice flow model. The statement ending in line 64 is therefore incorrect, as previous studies have taken this approach. A citation to Wirbel et al. (2017) should also be included.

This has been rectified in the text, thanks for pointing this out. The sentence was changed to:

"The pronounced effect of debris should not be ignored in numerical models to determine the future evolution of mountain glaciers, yet only few studies have included this complex process in time-dependent models (e.g. Jouvet et al., 2011; Rowan et al., 2015; Huss and Fischer, 2016; Kienholz et al., 2017; Rezepkin and Popovnin, 2018; Wirbel et al., 2018)."

>> Line 73: State glacier area here.

Done.

>> Line 96-98: Use metres for debris thickness values here to be consistent with the rest of the text.

Done.

>> Line 101: "Mean annual air temperature", and "+" is not needed before the values.

Changed.

>> Line 110: Explain what you mean by "1.5D" or stick with "1D" to indicate a flow line calculation. L112. Do you mean 2D rather than "3D", i.e. a matrix calculation?

The model only uses ice and debris flow in 1 dimension, namely along the x-axis. However, the remaining glacier area was also implicitly taken into account by using the width in the continuity equation. To avoid confusion, it was changed to *"numerical flow line model"*.

>> Line 224: Give value for H*debris, from Table 1, the value used after tuning was 1.15 m, which results in the steep curve mentioned in Major Comment 1. Also it is not clear as written here how this model compared to that presented in Anderson and Anderson (2016) as mentioned in the Introduction, which used a hyperbolic rather than exponential function to scale sub-debris melt; h*/(h*+hdebris) their Eq. 3 with h* of 0.065 m.

See major comment 2.

>> Line 258, 260: Unclear as written. What is the meaning of "±" before the values given for H*debris? Do these values range from –0.6 to 0.6 m?

The ± means *"approximately"*, and the text was adjusted accordingly'.

>> Line 259: One of the key references for a previous application of this model to Djankaut Glacier is Rybak et al. (2018), which is cited to justify parameter choices and to give detail about the model. However, this document is difficult to locate and appears to only be available in Russian. I was not able to use this reference to collect information about the model. At Line 259 the citation here is incorrect, as "Rybak (2018)" is not in the reference list.

We acknowledge that both Russian papers are hard to find and not easy to understand, and have therefore decided to remove these from the manuscript.

>> Line 363: All the models have different time steps; 3-hourly for the mass balance model, ~4 hourly for the ice flow model and ~4 days for the debris transport model. How are the integrated, and what impact do these time steps have on the result when the response time is ~30 years?

The time steps for the ice flow and debris models were chosen for reasons of numerical stability to satisfy the CFL criterion for diffusion and advection problems. The timestep of 3 hours for the mass balance model is required to capture the daily cycle and because the weather data were not available at shorter intervals. The mass balance is calculated for a full balance year, changing year per year. The choice of these time steps has a negligible impact on the results given the length response time of ca. 31 years.

>> Line 455-459: What evidence is there for the choice of debris input parameters?

These values represent a range of possible future scenarios informed by the past, as the location, release and magnitude of future debris sources can of course not be predicted. We added the following text after Line 459 for clarification:

"It must be noted that the values for these parameters represent a range of possible future scenarios, as the exact location, time and magnitude of future debris sources cannot be predicted."

>> Line 490: Incorrect statement, see comment on line 53 above.

Agreed. Changed to:

"… not yet integrated in numerical flow line models."

>> Line 508-518: Here and elsewhere, although the written text is generally clear and free of typographic errors, the writing style is rather vague and qualitative, using large lists of variables/controls without indicating their importance, and the meaning can be difficult to follow. The manuscript would benefit from editing to enable clearer, more precise statements to present the study and its results.

Noted.

>> Model code: The code and data used are described as available on request from the author. I believe the Cryosphere now requires these to be open access in a repository.

To comply with TC's data policy, we now make the model code publicly available via GitHub/Zenodo. The model code that served for this research can be found and downloaded from: https://github.com/yoniv1/Djankuat_glacier_model. The code placed here is a 1D coupled ice flow-debris cover model. It uses bedrock geometry together with a parameterized mass balance profile to calculate the ice thickness evolution on a grid with spatial resolution dx for the Djankuat Glacier, and also takes into account an evolving supraglacial debris cover until a steady state situation has been reached. Our code availability statement now reads:

"Code availability. Code availability. The coupled ice flow-supraglacial debris cover model for the Djankuat Glacier used in this research was written in MATLAB_R2019a. It can be downloaded from the GitHub repository at: https://github.com/yoniv1/Djankuat_glacier_model, doi: https://doi.org/10.5281/zenodo.3934612."

Newly added references

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Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. I., Quincey, D., Thompson, S., Toumi, R., and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards, Earth Sci. Rev., 114, 156–174, doi:10.1016/j.earscirev.2012.03.008, 2012.

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Zekollari, H., Huss, M., and Farinotti, D.: Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble, The Cryosphere, 13, 1125–1146, doi: https://doi.org/10.5194/tc-13-1125-2019, 2019.