Response to reviewer comment #1. Note reviewers' text is shown in **blue**, with responses in **black**.

General comments:

Pletzer at al. present a point-based optimization and evaluation of a simplified version of the WRF-Hydro/Glacier modelling system over the McMurdo Dry Valleys (MDVs) using forcing data from automatic weather stations. They identify two aspects of the cryospheric component needing improvement for accurate simulations of runoff, namely the representation of percolation in ice layers and the parameters in the albedo scheme. The manuscript is well-written and organized, the results are clearly and concisely presented, and the topic suits the scope of the journal. However, I have a concern about the novelty and wider applicability of the presented results due to the simplified model configuration employed, as outlined in my major comment below, which should be considered prior to publication.

We express our gratitude for taking the time to review our manuscript and offering valuable feedback for its improvement. We have taken your comments into consideration and made significant revisions. Specifically, we have reworked the introduction that includes a new and much clearer research aim, and conclusion to explicitly highlight the scientific advancement of our research. To eliminate any confusion regarding the motivation for the analysis, we have added a schematic of the WRF-Hydro/Glacier modelling framework. Additionally, we have addressed the minor comments provided. Thank you once again for your time and insightful input.

Major comment:

As I understood, the authors only used the cryospheric (Crocus) and land-surface (Noah-MP) modeling components from WRF-Hydro/Glacier. The presented work is therefore mainly small changes to/calibration of parts of Crocus, which is an important foundational step for tackling interesting science questions in a new region but is itself a methodological task. As a result, the introduction lacks a clear scientific question and, in my opinion, the results may be insufficiently novel, as previous studies have applied Crocus in Antarctica (including in coupled simulations; e.g., Brun et al. (2017) https://doi.org/10.3189/002214311797409794) and performed point surface energy/mass simulations in the MDVs (line 383).

The authors argue for the standalone approach to "limit uncertainties in meteorological forcing data introduced when coupled to WRF" (line 144), however observational data also contain uncertainties (e.g., the discussion around deriving solid precipitation from SR50s). More importantly, this simplification means that the capability of the full WRF-Hydro/Glacier modelling system has not been assessed and leaves open the question of how the presented modifications impact simulated runoff in coupled simulations when changes in surface conditions can feedback on the atmospheric forcing.

I suggest that the authors either provide a stronger justification for their approach and/or more clearly communicate the novelty and advancement in scientific understanding of their work, or ideally include additional experiments with the full WRF-Hydro/Glacier model (for example, comparing oldrunoff_oldalbedo and newrunoff_newalbedo in an interactive context). The latter suggestion would greatly strengthen the impact and novelty of the manuscript.

As suggested we have clarified the novelty and advancement of the research presented in our manuscript, as well as explaining the rational of the methodological approach by adding a schematic of the modelling framework and reframing the introduction, defining a new research aim and reiterating how this work has advanced knowledge in the conclusion. Importantly, this research provides a platform to conduct fully distributed hydrological modelling in the MDV.

Research Aim

To ensure readers understand the motivation and importance of this research we have re-written the introduction, and modified the research aim to: "The aim of this study is to optimise a multi-layer snowpack scheme (Crocus), that is integrated in WRF-Hydro/Glacier, to resolve the onset, duration and end of melt over a cold-based glacier in the MDV of Antarctica." It is now clear that the major contribution of this work is to develop the snow and ice modelling component embedded in WRF-Hydro/Glacier, to ensure the physical processes governing melt are resolved in the unique environmental setting of the MDV. What sets this research apart from previous work is that the snow and ice modelling is embedded into WRF-Hydro/Glacier, which allows the routing of meltwater into the surrounding landscape to be resolved for the first time. This research provides the stepping stone to achieve this more ambitious goal.

Novelty

Previous point-scale energy and mass balance modelling in the MDV (Hoffman et al., 2008; Macdonell et al., 2013; Hofsteenge et al., 2022) have used observed albedo to force their models. The use of observed albedo prevents simulations being performed to determine how runoff may change in a future climate and/or extending runoff simulations into areas without albedo measurements. We carefully tune an interactive spectral albedo scheme based on detailed spectral measurements from Antarctica to successfully simulate the temporal evolution of albedo for the first time in the MDV. Importantly, the new modelling framework provides a platform to assess the connections between the atmosphere, glaciers, bare-land surfaces and soils, stream channels and lakes in the future. To do so, we must first modify WRF-Hydro/Glacier for this region. Importantly, our modelling framework allows us to show previously unresolved feedbacks between albedo, melt and snowfall.

As noted by the reviewer, Brun et al. (2011) applied Crocus in Antarctica at Dome C. However, Dome C does not have melt since surface and near surface temperatures never exceed −20 °C. They show that Crocus simulates the snowpack well over a 11-day period, but they do not have melt or wet snow conditions. Here we identify that, in order to successfully apply Crocus to melting conditions on a cold-based Antarctic glacier, it is necessary to modify the percolation of water through ice to correctly represent near surface runoff, in addition to the previously mentioned modifications to the albedo scheme. We show that modelling albedo and near surface runoff are crucial to simulating the evolution of the glacier during the melt season. As noted above, this work provides a platform for future work to improve our understanding of hydrological connectivity in the MDV and other ice-free Antarctic regions.

Methodological choices

We chose to use the WRF-Hydro/Glacier modelling framework rather than just Crocus due to the coupling with the hydrological modules. This modelling framework moves beyond previous work and is capable of pushing the boundaries of any modelling framework for melt and hydrological modelling in this region. This opens up potential for future studies to fill the gap in modelling the hydrological connectivity, however that would not be possible without being able to model the water source on this unique environment. This study shows the necessity of modifying WRF-Hydro/Glacier for cold-based glaciers to accurately simulate melt.

We chose to focus on the snowpack module forced by automatic weather station data at a point on the glacier to limit input uncertainty in the model and demonstrate that the model is able to simulate melt accurately. Using gridded atmospheric data (either from numerical weather prediction models or interpolated from AWS) to force WRF-Hydro/Glacier introduces additional uncertainties. WRF-Hydro is a hydrological model, and it is rarely run in coupled simulations with an atmospheric component (i.e., the WRF model). For example, recent papers focus on so called “standalone simulations” e.g., Xiang et al. (2017), Eidhammer et al. (2021), Lahmers et al. (2021), Pal et al. (2021), Cerbelaud et al. (2022), Mehboob et al. (2022) and many others. We have clarified the choice of model configuration and added a schematic to clarify the modelling framework and which components were used in this study – see the in text changes below. The new schematic clearly shows readers that the primary coupling in WRF-Hydro/Glacier is between the land surface models and terrain routing modules rather than between atmospheric and glacier.

Text changes:

We have provided a stronger justification and highlighted the novelty of this research in the Introduction and Conclusion, including refining our research aim. As noted, we have also added a schematic of the WRF-Hydro/Glacier modelling framework to clarify the model setup and components used in this paper.

We changed the Introduction to:

1 Introduction

Terrestrial Antarctic ecosystems exist almost entirely in ice free regions. Under the highest emissions scenario, RCP 8.5, climate studies show that these ice-free regions may increase from 1% of Antarctica to almost 25% by the end of the century (Lee et al., 2017). Given the anticipated increase in ice-free regions in Antarctica, there is an urgent need to better understand the sensitivity of the McMurdo Dry Valleys (MDV) to climate variability and change. The MDVs are currently the largest ice-free areas in Antarctica and home to a unique microbial ecosystem that resides in a system of streams and lakes situated in the valley floors. This ecosystem is dependent on fresh water that is sourced from glacial melt (Gooseff et al., 2011) for survival. It is expected that the biogeography of this ecosystem will be altered in response to the larger changes in climate impacting Antarctica, thus it is key to understand and simulate how atmospheric warming will impact glacier melt and the hydrological connectivity of this unique environment.

Unlike most mid-latitude glaciers, the glaciers in the MDV are mainly cold-based, meaning that the subsurface temperatures are below the pressure melting point and ice is frozen to the bedrock (Fitzsimons, 1996; Gooseff et al., 2011; Fountain et al., 2016). MacDonell (2008) was the first to study the full hydrological drainage system and developed a conceptual modelling framework for cold-based glacial meltwater drainage processes on Lower Wright Glacier in the Wright Valley. This study identified the need for a physically based, rather than empirical, model to simulate the complex drainage systems of MDV glaciers (MacDonell, 2008). Hoffman (2011) was the first to implement a distributed surface energy balance model and investigated the spatial and temporal distribution of mass and energy exchanges of several glaciers in Taylor Valley. This study showed that penetrating shortwave radiation and meltwater drainage are important for accurately modelling surface ablation on glaciers in the MDV (Hoffman, 2011). Cross et al. (2022) extended this work by coupling the glacier energy balance model used by Hoffman (2011) with a lake energy balance model to assess lake sublimation and the water budget. Whilst both Hoffman (2011) and Cross et al. (2022) model glacial runoff, neither explicitly model the off-glacier processes in the hydrological system, such as streams or soil moisture.

Similar to mid-latitude glaciers, glacier melt in the MDV is driven primarily by net radiation, which is sensitive to variability in solar radiation. What is different in the MDV is that energy and mass exchanges are often very small, with minor changes in the surface energetics capable of shifting the hydrological system from a frozen state to one that is melting. Thus, small changes in energy (for example, through albedo) can have a very large impact on melt generation (Hoffman et al., 2008; Macdonell et al., 2013). It has also been observed that solar radiation penetrates the top 5-15 cm of the snow or ice surfaces on the glaciers in the MDV (Hoffman et al., 2014) and this near-surface layer can retain heat longer than the surface due to the solid-state greenhouse effect (Brandt and Warren, 1993). This effect extends the duration of melt events and model simulations suggest melt from this layer can be an order of magnitude larger than surface melt (Hoffman et al., 2014). Despite solar radiation being crucial for modelling melt, no study has attempted to simulate the variability of albedo over the duration of a full melt season in the MDV. To ensure the magnitude and duration of melt is captured sufficiently in a low energy, polar environment like the MDV, it is critical that glacier albedo is modelled accurately.

To resolve the hydrological connectivity in the MDV it is necessary to identify the pathways of meltwater from the glaciers to the bare-land surfaces that surround them, including understanding how water is channelled into stream networks and stored in the numerous closed-basin lakes. The WRF-Hydro/Glacier modelling framework (Gochis et al., 2020; Eidhammer et al., 2021) provides an opportunity to physically model the hydrological cycle in the MDV due to its ability to resolve the connections between the atmosphere, glaciers, bare-land surfaces and soils, stream channels and lakes (the hydrological reservoirs). WRF-Hydro/Glacier contains a detailed snowpack model (Crocus), which is fully coupled with a distributed hydrological model (WRF Hydro). Importantly, the model provides enough flexibility to be able to resolve the meltwater pathways from the glaciers to the surrounding landscape, which is critical given the glaciers, which are the primary hydrologic reservoirs, are controlled by the daily, seasonal, and annual cycles of the surface energy balance (Gooseff et al., 2011). Importantly, WRF-Hydro/Glacier can be applied at small catchment scales up to continental scale domains, providing fully-distributed hydrological modelling opportunities in the MDV and the larger surrounding regions. Eidhammer et al. (2021) implemented WRF-Hydro/Glacier on a temperate Norwegian glacier and demonstrated that the model was capable of simulating the mass balance, snow depth, surface albedo and runoff when compared to observations. However, the environmental setting of the cold-based MDV glaciers is vastly different from the temperate glaciers in Norway, with the dry polar climate of the MDV ensuring that summer melt generated from variability in the surface energy balance has a much stronger control on the hydrological cycle than precipitation.

Given the importance of the surface energy balance to meltwater generation, the modelling of albedo and near-surface melt on the MDV glaciers is critical. The detailed snowpack scheme in Crocus, which is integrated in WRF-Hydro/Glacier, has been implemented in a range of environments (Vionnet et al., 2012), including extremely cold (well below the melting point) conditions over the Antarctic ice sheet (such as Dome C) (Brun et al., 2012) and high precipitation (both rain and snow) and relatively warm and melting conditions on temperate glaciers (Eidhammer et al., 2021). However, the challenge in implementing it on glaciers in the MDV is that the surface energy balance is more dominant than precipitation (snowfall) in governing variability in mass balance, largely through its influence on controlling melt and the associated feedbacks on surface albedo. The implication of this is that runoff and streamflow are entirely sourced from glacier melt rather than from precipitation (rainfall), as is common on temperate glaciers. In this context, the aim of this study is to optimise a multi-layer snowpack scheme (Crocus), that is integrated in WRF-Hydro/Glacier, to resolve the onset, duration and end of melt over a cold-based glacier in the MDV of Antarctica. If melt is sufficiently resolved in this modelling framework it will allow the pathways of meltwater to the surrounding landscape (the other hydrological reservoirs) to be resolved at different spatial and temporal scales in future applications of WRF-Hydro/Glacier.

To achieve our primary aim, WRF-Hydro/Glacier is implemented at a point on Commonwealth Glacier in the Taylor Valley, forced by automatic weather station data and tested against observations of broadband albedo, surface and near-surface ice temperatures, surface height change and streamflow. Given it is the first time this modelling framework has been implemented in this unique environmental setting (cold-based glacier, energy balance dominates over precipitation, limited opportunities for melting threshold to be reached) it was necessary to modify the percolation of water through the glacier and the spectral albedo scheme to accurately simulate the feedbacks between albedo, snowfall and melt. The limited energetics and complicated pathways for water transport in this environment makes testing at a point scale using observational rather than modelled input data a critical first step towards modelling the full hydrological connectivity of glacial meltwater in the MDV.

The next section describes the WRF-Hydro/Glacier model setup and initialization. Section 3 describes the site and the observational data used to force and validate the model. Section 4 details the modifications to the Crocus snowpack meltwater drainage and spectral albedo schemes necessary to adapt the model to the unique cold-based glacial environment of the MDV. Section 5 compares the performance of the original and modified versions of the model to observational data over the 2021/22 melt season, while Section 6 reflects on the significant advances made to WRF-Hydro/Glacier in this study and the platform it provides to resolve the full hydrological system in the MDV.

Other key changes

To ensure the modelling framework is clear to readers we added a new figure of WRF-Hydro/Glacier in Section 2.1. This shows where the coupling is between different modules, and removes any uncertainty about the meteorological forcing data used in this study:

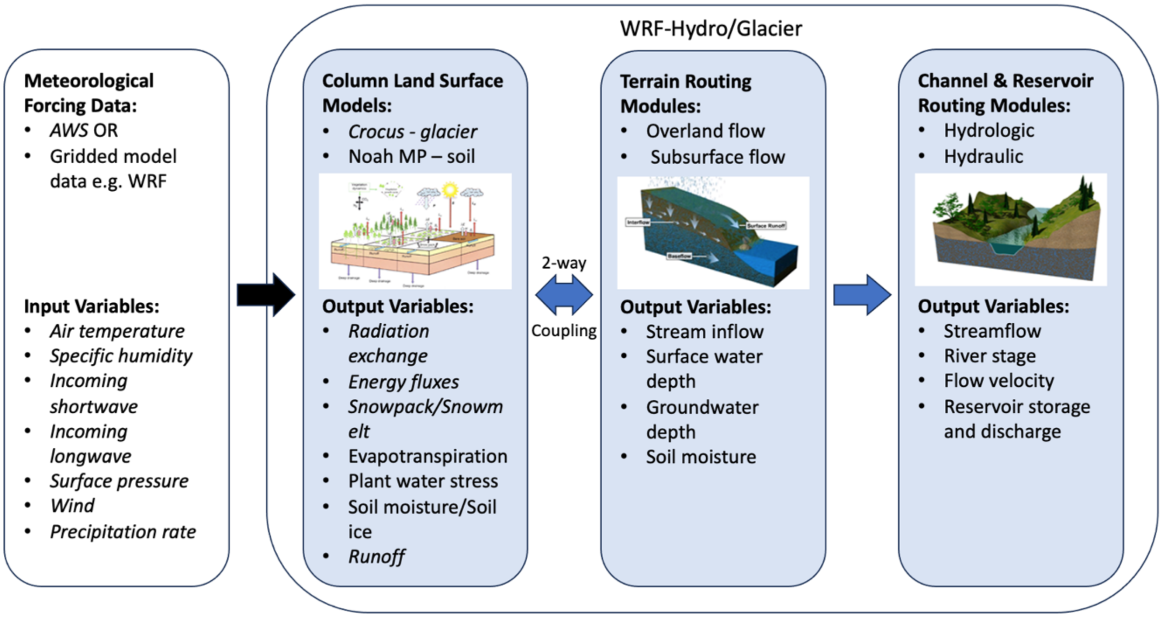

Figure 1. Schematic of the WRF-Hydro/Glacier modelling framework. Modules and variables used in this study are displayed in *italics*. Adapted from NCAR (https://ral.ucar.edu/sites/default/files/public/WRFHydroPhysicsComponentsandOutputVariables.png, last access: 8 August 2023).

Changed Line 383: "Although previous studies have implemented surface energy and mass balance models at specific points on MDV glaciers (Hoffman et al., 2008; Macdonell et al., 2013; Hofsteenge et al., 2022), they have neglected to simulate albedo. Implementing WRF-Hydro/Glacier allows us to fill this gap and show that simulating albedo is necessary for simulating the feedbacks between albedo, snowfall and melt in the MDV."

Changed lines 400-408:

Conclusion

For the first time, we have simulated the evolution of albedo over a melt season in the MDV. We found it was necessary to modify two schemes to reliably simulate the surface energy balance and runoff of a cold-based MDV glacier:

- The percolation of meltwater through ice layers was modified to allow near-surface runoff, and
- The spectral albedo parameters for both snow and ice were modified based on observed spectral signatures enabling the evolution of broadband albedo and net shortwave radiation to be resolved.

With these modifications, we were able to accurately simulate the feedbacks between albedo, snowfall and melt, which is critical in resolving the onset, duration and end of melt over a cold-based glacier in the MDV. The changes implemented allowed the subtle changes in energy available for melt to be resolved over the course of the ablation season, which would have otherwise not been achievable. Importantly, this is the first time a detailed snowpack model has been coupled to a fully distributed hydrological model in the MDV and represents a significant step towards understanding streamflow dynamics and modelling the full hydrological connectivity of glacial meltwater in the MDV at different spatial and temporal scales.

Specific comments:

1. The fact that the manuscript presents a standalone simulation without the atmospheric or streamflow components should be more consistently communicated. Although the AWS forcing is mentioned in the abstract, this simplification is not clear from the title or from using the full model name throughout the paper. Statements like „the first application of WRF-Hydro/Glacier model in MDV“ (line 5) while technically correct also do not communicate the nuances of the presented work.

As discussed above, WRF-Hydro is primarily a hydrological model, and is not commonly run interactively with the WRF atmospheric model. We have clarified this by adding the schematic of the WRF-Hydro/Glacier modelling framework (Fig. 1) as shown above. We have opted to keep the title as it is important to communicate to readers that we are using the WRF-Hydro/Glacier modelling framework (rather than the snowpack model on its own). We also mention in the title that the model is applied to "a cold-based Antarctic glacier" and that is where the point of interest is located. There are also no on-glacier runoff measurements to validate the runoff from WRF-Hydro/Glacier, so we have opted not to present this.

We have amended Line 5 to: "the first application of WRF-Hydro/Glacier with an embedded multilayer snowpack model at a point in the MDV."

2. Please provide information about the extent and location of the 200-m computational grid and how the point AWS data was distributed spatially over this grid. However, it would be worth mentioning why this grid was used when the two active components (Crocus and Noah-MP) are column models without any lateral interactions and the analysis is point-based.

We agree that mentioning the grid size is confusing to readers and we have removed it as this study is conducted at a point.

We changed Line 145 to: "In this model experiment, we used the Crocus snowpack model embedded in WRF-Hydro/Glacier V5.2.0. Crocus was forced by observed meteorological data at an hourly time step and analyzed at a point on Commonwealth Glacier."

We maintain the description of the distributed model in Section 2.1 as the hydrological modules are spatially distributed and it displays the future uses of the model. The modifications presented in this study can also be applied spatially or in different regions with cold-based glaciers – this is precisely why this model was chosen.

3. Please provide information on time periods for spin-up vs simulation, calibration vs evaluation, and CWG vs COHM forcing earlier in the methods and in one place for convenience (e.g., in a table).

Added to Section 3.3:

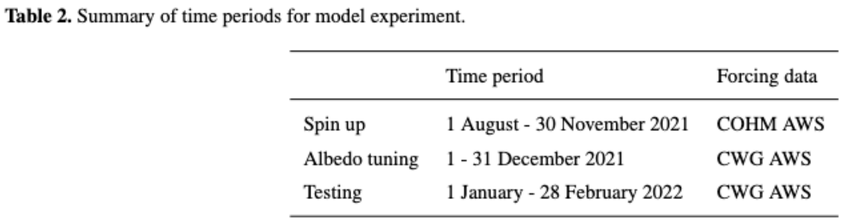

Table 2. Summary of time periods for model experiment.

	Time period	Forcing data
Spin up	1 August - 30 November 2021	COHM AWS
Albedo tuning	1 - 31 December 2021	CWG AWS
Testing	1 January - 28 February 2022	CWG AWS

4. Section 2.1: Please provide more detail about what running in standalone mode means in terms of active components and/or interactions.

As shown above, we have added a schematic of the WRF-Hydro/Glacier modelling framework (Fig. 1) in Section 2.1 to clarify how the components of the model interact and are coupled.

Standalone mode means the land surface model is forced by the atmospheric data, rather than coupled to an atmospheric model. We removed this term in Line 69: “The model can be either forced by meteorological data or other gridded atmospheric data.”

To improve the clarity, we also changed Line 144 -145 to: “In this model experiment, we used the Crocus snowpack model embedded in WRF-Hydro/Glacier V5.2.0. Crocus was forced by observed meteorological data at an hourly time step and analyzed at a point on Commonwealth Glacier. The high-quality observational data obtained on Commonwealth Glacier reduces uncertainty that might be introduced by using model or gridded data as forcing data.

5. Line 150: Four months seems short for spinning up ice temperatures in a 50 m column based on my experience with the heat equation. Which objective criteria were used to determine if this period was sufficient?

The purpose of this study is to apply the WRF-Hydro/Glacier modelling system at a point, identify where the model needs modifications for this unique environment and provide robust solutions to ensure the onset, duration and end of melt are resolved. As noted in Lines 149-150, the ice temperatures are initialized at the mean annual temperature of -18 °C, from Obryk et al. (2020).

We changed Line 153 to: We analyzed ice temperatures at the end of the spin-up period and found that the difference between observed and modelled ice temperatures at a depth of 0.05, 0.1, 0.2, 0.5 and 2.0 meters at the beginning of December are less than 1 °C, which is within the sensor uncertainty shown in Table 1.”

In Figure 8, it seems the biases change systematically in time (i.e., the cold bias at depth decreases while at upper levels it increases). Could this feature be attributable to spin up (which could be assessed with sensitivity runs) or e.g., the changing depth of the temperature sensors?

TC1 and 2 melted out of the glacier shortly after December 15. Thus, we think that this is likely more due to the changing depth of the sensors, rather than the model spin-up.

6. How was the snow depth and density profile initialized?

Added to Line 148: “Snow depth was initialized as 0 m and the layers were initialized with a constant density of 900 kg m^{-3}.”

How well are snowpack conditions represented at the end of the spin-up period and how might this influence the simulated albedo?

As mentioned in Q5, the ice temperatures were within the measurement uncertainty of the thermocouples. From the surface height record, we can see that there was a snowfall event at the end of November just before the start of the simulation (also shown in Fig. 9 (now Fig. 10)). At the end of the spin-up period, surface height is 1.4 cm higher than at the start of the spin-up and the top layers are snow with a density of 131 kg/m^3, 118 kg/m^3 and 786 kg/m^3 and the layers below have a density of ice. This ensured that the modelled albedo in Fig. 4 (now Fig. 5) (both in observed and newalbedo) at the start of the simulation is well represented. This is critical for modelling the feedbacks between albedo, snowfall and later in the season, melt.

7. Line 276: how was the absence of overfitting assessed?

We agree that the term overfitting could cause confusion to readers and have removed this. We have removed Line 276 and changed Line 275 to “The newalbedo model better captures the variability in observed albedo over the melt season with a root mean square error of 0.08 compared to oldalbedo with a root mean square error of 0.35.”

Suggestions for technical corrections:

1. Line 14: Remove „of melt“

done

2. Table 1: Is it relevant to provide detailed information on instrumentation for COHM as well?

Added to Line 114: “The accuracy of the sensors are similar to CWG AWS and the instruments are detailed in Gooseff et al. (2022).”

3. Line 214: Please clarify that you are referring to the Crocus snow albedo scheme

done

4. Line 300: How do you define slight? The cold bias is ~2 K

Added: “has a cold bias of up to 2 °C”

5. Line 307: „a cold bias and a phase shift“

done

6. Line 328: Rephrase „similar“ as surface height changes range approximately an order of magnitude

Changed to: “After 23 December, the rate of decrease in the change in surface height across the three models stabilizes and is less than before. From this point to the end of the simulation, oldrunoff_oldalbedo model has 90 cm ablation, while newrunoff_oldalbedo has 10 cm ablation and newrunoff_newalbedo has 3 cm ablation compared to 10 cm observed ablation.”

7. Line 350: Rephrase „ephemeral,“ as the term may not be accessible to a wide audience

Changed sentence to: “On the other hand, the newrunoff_newalbedo model runoff has less runoff overall and the runoff drops to zero frequently compared to the newrunoff_oldalbedo model, which has runoff every day from the start to end of the season.”