Response to reviewers

Anonymous referee #3

We thank the anonymous reviewer for his review and constructive comments on our work. We reply to his/her general and specific comments below.

General Comments

-Throughout the manuscript there was no mention of handling of inversions for the calculated lapse rates from the AWS on the glacier and from the permanent weather stations. Is this due to the authors not finding the occurrence of inversions in their study area. Please add in the discussion the implications of inversions in the calculated lapse rates.

Reply: we did not have vertical temperature profiles to address this directly. But from the on-glacier temperature sensors distributed across the glacier we found no evidence of systematic inversions (i.e. positive lapse rate) during summer (May-August, see our Figure 5a). Outside the glacier, monthly lapse rates were also consistently negative.

We checked lapse rates calculated on an hourly basis on the glacier. Inversions were found to occur only 1.7% of the time during the May-August period. We added this information in section 4.3 (lapse rates):

Stronger daytime down-glacier winds, possibly driven by a larger thermal gradient between the lower ice-free valley and the glacier, could result in down-glacier cooling and correspondingly shallower near-surface lapse rates or **even inverted lapse rates**, as shown on neighbouring Athabasca glacier (Conway et al., 2021). **Closer inspection of hourly lapse rates revealed that inversions only occurred 1.7% of the time between May and August on Saskatchewan Glacier and that the mean diurnal cycles represented well the bulk of lapse rate variability.**

-Elevations of the permanent weather stations barely covers the elevation gradients over Saskatchewan Glacier. The authors do a good job of discussing this and pointing out that the higher elevation above 2900 m represents only 8% of the accumulation area and therefore has small impact on the overall simulated mass balance. But it remains a weakness of paper. In the discussion it would be prudent to compare results of precipitation downscaling from other studies such as Jarosch et al. 2012 to understand if more complex methods would better resolve precipitation trends for a further justification of the use of a statistical downscaling method.

We added the following section to the discussion:

The station-free, linear orographic model for precipitation (LOP) method used by Jarosch et al. (2012) might perhaps be better suited than station-based downscaling in steep topography. The authors reported an improvement of the median relative error (*M* = -3.1 to -20.9%) with respect to monthly precipitation totals in the Canadian Rockies, compared to raw NARR which underestimated station precipitation (*M* = -9.5 to -42.6%). However, the median absolute error (*MAD*) of the relative error did not change much, and even increased in some instances, i.e. from 13.5-31.3% for the raw NARR compared with 19-29.5% for LOP (see table 3 in Jarosch et al., 2012). The station-based scaling used in this study resulted in *M* = 3.8% and *MAD* = 33%, compared to *M* = 27% and *MAD* = 41% for the raw monthly NARR precipitation. Hence the improvement seen is greater than that reported for the station-free LOP model by Jarosch et al (2012) in the Rockies.

-Presentation of the results between fixed and dynamic glacier mass balance results remains unclear throughout the manuscript. Earlier on when discussing the topographic data, it should be mentioned the negligible effect of the conventional glacier simulation and therefore only the reference mass balance simulation results are presented for final glacier mass balance results.

The text explicitly states when the reference vs conventional mass balance is used. We have reviewed the text to add some more clarifications, e.g., in section 4 and in Figure 8 caption to make it clear that long-term simulation of past mass balance are conventional balances, i.e. including changes in glacier area.

Specific (Line by line):

Title: Modelling glacier mass-balance and climate sensitivity in a context of observations: applications to Saskatchewan Glacier, western Canada -> Modelling glacier mass-balance and climate sensitivity in a context of sparse (or limited) observations: applications to Saskatchewan Glacier, western Canada

Yes that was actually the title… not sure why the word ‘sparse’ was not there. It is there now.

Line 19: was little -> was a little

Changed to ‘not very sensitive’

Line 120: (ii) should this objective also include the air humidity and albedo feedback as they are the major conclusions of the paper?

I agree, changed to: ‘quantify the respective contributions of energy balance, precipitation phase **and humidity** feedbacks to the mass balance climate sensitivity warming scenarios’;

Line 89+120: spare -> sparse

corrected

Figure 1: Reduce the interval of labeled contours. Increase font size on Fig. 1c legend. It is not immediately clear the location of the air temperature points, since the color of the star is overlapped with the snow survey points – change the symbol of the air temperature point or increase the size of the symbol.

Done

Line 195: Why were the precipitation records from the other five permanent weather stations not used?

Because they were the two closest, and highest elevation ones. All 7 stations were used to derive lapse rates, as mentioned in that section. We modified the sentence to emphasize: the choice of stations to use for downscaling:

‘As precipitation was not measured at the AWS site, a historical precipitation record was produced using data from the two weather stations closest to Saskatchewan Glacier and highest in elevation ….’

Line 209: State the temporal and spatial resolutions of ERA interim and NCEP reanalyse products.

Modified to: ‘ERA interim (6-hourly, ~80 km resolution) and NCEP (6-hourly, ~ 600 km resolution) reanalyses’

Line 337: te -> the

corrected

Line 353: Says depth scales was calibrated with snow depth at AWS but section 3.2.1 does not describe recording snow depth measurements. Although the supplementary material describes snow depth sounding measurements. Clarify where the snow depth measurements are coming from.

Information was added to methods section 3.2.1: Recorded variables include air temperature (T_a), relative humidity (*RH*), incoming global (*G*) and reflected (*SW*↑) solar radiation, wind speed (*WS*) and direction (*WD*) and **snow depth using an ultrasonic sensor.**

Line 358: bias correction -> downscaling?

No, we used the word ‘downscaling’ to describe the spatial interpolation of NARR to the station and the bias correction of the NARR. That section describes the bias correction step.

Line 419: I think this should be from 0 to 7 °C to be consistent with results and abstract.

Yes. Corrected

Line 421: Define GCM at first mention

Done

Figure 5: Are the values correct for relative wind direction on Fig. 5a? If so, why do they vary from the monthly wind directions?

Yes they are correct. Panel A is the mean diurnal cycle averaged over the whole period, panel B are monthly cycle averaged over the same period. The average of the two curve is the same (12 degrees).

Line 546: Mention the ultrasonic snow depth sounder in section 3.2.1

Done

Figure 6: check the figure caption for correct lettering of figure numbers.

Corrected

Figure 6d: Shows the limitations of the precipitation gradient since the gradient derived is not within the same elevational ranges and should be discussed further as per previous comments.

Yes, but Figure 6d also shows that except for 2014 the observations fit the simulated profile. This is extensively discussed in section 5.2

Line 580: Dynamical adjustment explanation should be explained in the methods somewhere between lines 180 and 185.

The description of the calculation was moved to there as suggested

Line 595: The use of lapsed interpolated should be reworded for clarity to ‘lapse rate corrected’.

Corrected as suggested

Line 611: 'an even more so ice surface morphology' reword to clarify if you mean that the surface morphology is more uneven than the snow surface or less uneven.

Corrected to: and even more so on rougher ice surface morphology

Line 800: Include that there was difference in elevational ranges used for precipitant gradient compared to the elevation of the Sask. Glacier.
I do not think it is relevant there as we are discussing downscaling performance at the Columbia/Parker Ridge station so that lapse rate extrapolation is not concerned here.

Line 941: The air humidity feedback is one of the main findings from the paper, expand on the implications for glacier mass balance at Sask. Glacier with increasing atmospheric warming from this feedback.

We added this sentence: Under a stable atmospheric moisture regime, increasing atmospheric warming would lead to an increasing humidity feedback on ablation (Table 1).

Supplementary Martial:

- 'Errors in glacier outline delineation were not considered' Please provide justification for why they were not considered.

Changed to: Errors in glacier outline delineation were not considered as they are assumed small compared to other sources.

-Figure S1: interesting to see Lake Louise precipitation data included here. Did you compare the record with Columbia and Park Ridge to show the variation? Include a few sentences to say why the Lake Louise and other precip record was not included in the study.

The station is somewhat far from the glacier and at a comparatively low elevation to be used as model forcing. Figure S1 does just that (the comparison with Columbia/Parker), on a climatological scale (seasonal).

We added this sentence: 'Only the Columbia and Parker Ridge station, located close to the glacier and the highest elevations (2000 m), were used for downscaling NARR precipitations, while the other stations were used to constrain the precipitation lapse rate.'

--END OF REVIEW------------------------------------

Referee #4: Andrew MacDougall,

Overall evaluation:

The study uses a distributed energy balance melt model forced with reanalysis data to simulate the mass balance of Saskatchewan Glacier. The model is able to reasonably reproduce the mass balance for the years that data is available, and longer-term averages of mass balance derived from geodetics. The paper is well written and has of complete description of the data-set, models, and analysis used. The authors have responded well to the previous set of comments from other reviewers have found no scientific flaws in the analysis. It is good to see progress being made on glacier melt modelling. Overall I recommend that the paper undergo minor revisions.

We thank Dr. MacDougall for his review of our work and previous evaluation reports. We reply to his general and specific comments below.

Specific comments:

Line 19: "was little sensitive" is unclear. Rewrite for clarity.

Changed to: 'Not very sensitive'

Line 29: Seems like there should be a time unit as part of the temperature sensitivity e.g. 'm w.e. ºC a-1'?

Correct, we added the a^{-1}

Line 34: Climate warming increases the global total amount of precipitation. So whether a region gets more snow or less snow is complex and is expected to vary byregion.

Correct. We reworded to : reduced precipitation as snowfall in cold regions

Line 89: Should 'spare' be 'sparse'?

Yes, corrected

Figure 1: Legend is panel C is too low-resolution to read. Need a higher resolution (or vector format) version of this figure.

The legend was improved, font sizes were increased

Line 145: -10.1?

Yes, corrected

Line 210: Change 'represent well' to 'well represent'

Change done

Figure 5: Be careful here with colour-blind compliance. The green and the red are probably to close.

We checked and it seems the contrast seems compliant…

Figure 9: Restate the abbreviations in the figure caption.

Done

Figure 12: Two panels are labelled 'a'

Corrected

Line 842: Change 'reached in' to 'reached for'

Corrected