Response to Referee 1: Using GRACE to derive corrections to precipitation data sets and improve modelled snow mass at high latitudes

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We thank the reviewer for their comments and suggestions. In response to the main concerns:

i) In the course of the analysis, we have indeed investigated the overall water balance (eg. we have included the GRDC basin discharge and GLEAM evapotranspiration in Fig S10 in the Supplementary Information (labelled "Observed"). However, we have not explicitly shown the total water balance including the GRACE TWS term. We will provide more information about the overall water balance and add plots to the Supplementary Information. Note that the overall "observed" water balance (calculated using GRACE, GRDC and the precipitation datasets) does not close, which supports the suggestion of a low bias in the precipitation.

ii) Biases, broadly similar to those seen in JULES, have also been found in other models – see references in our Introduction (particularly page 3, line 12 and the preceding paragraph). This supports the idea that at least some of the bias is due to the input data, but does not rule out the possibility that the JULES model is a source of systematic bias. While we show that using the scaled precipitation does improve the representation of SWE in JULES, it does not completely remove the biases in all basins and for all driving data sets. Some of this remaining bias is likely due to model uncertainty. We will add more discussion of this to the text.

iii) We agree that issues related to energy fluxes and thermal state can also impact the modelled hydrology. While that is potentially a broad topic, we feel that in the context of our work these effects are less significant for the relatively high-latitude areas that form most of our study area. Winter conditions are severe in these areas and the land surface (including near-surface soil) is frozen for several months of every year. In terms of the development of the snowpack, the thermal state of the ground might be expected to play a more important role in the shoulder seasons (and at lower latitudes) – e.g. warm ground might slightly delay the deepening of the snowpack. However this effect will be relatively small in these very cold regions that reliably freeze every year and will have little impact on the seasonal maximum SWE in comparison to the effects of biased winter precipitation inputs.

In the following, we will respond to selected specific comments. All others we consider to be useful advice and will implement changes and expand explanations as recommended.

1 Abstract

Line 17 Re our emphasis on and comparison of maximum SWE and river discharge in the abstract. We are slightly unsure as to the meaning of this question. We emphasise these quantities because they are central to our study and closely related. If the question is why *maximum* SWE and discharge, as discussed in the manuscript we expect the maximum SWE (i.e. close to end of accumulation season) to be closely related to discharge, particularly the spring flood which is such a large component of the annual discharge cycle in these rivers.

2 Introduction

Page 9, Line 32 – Page 10, Line 1: The model does not simulate a transition state — the precipitation is either rainfall or snowfall. It could be possible to have a transitional range of temperatures but this has not been implemented in JULES. The literature on this subject suggests that the details of the transition are themselves highly uncertain and vary with atmospheric conditions.

Page 13, Line 4 – 5: The SWE from JULES is less sharply peaked but we do not know why. It is possible that this is a feature of the wintertime meteorological driving data (possibly a particular bias towards missing smaller events towards the end of the accumulation season) and/or of how the model responds to those particular conditions (possibly it tends to start to melt slightly too early).

Page 17, Line 28: Undercatch correction is a known issue for rainfall as well as snowfall, therefore we surmise that it may also be an issue in the summer in these basins. See for example [1] and [2].

Page 19, Line 1 – 2: We did not save the interception values from the model. However, this would be instructive, so we could re-run the model and allow it to output the interception to add to the discussion.

3 Discussion

We selected the maximum SWE as the variable for evaluating the model as this is most closely linked to the water that is available for the spring melt and therefore the overall water balance. The starting date of snow accumulation is less important for seasonal/annual water balance calculations and is possibly more dependent on temperature regime than available precipitation.

The effect of antecedent water storage on the SWE will likely affect the start of accumulation, as it will change the heat capacity and therefore whether the snow melts or stays frozen. However, we think this is likely to have a small effect – see discussion under 'Abstract' above.

4 Figures

Figure 2: We define the cold-season accumulation period to be October-February. This is defined based on two metrics

1. The change in GRACE TWS (ΔTWS) must be positive
2. The evaporation must be small

See Fig S4 for the fluxes. The reason that we do not include March is that the inter-annual variability is quite high, and in some years and some basins, the metrics above are violated in March. We chose a conservative accumulation period that would apply over all years and basins.

References

[1] Jennifer C. Adam and Dennis P. Lettenmaier. Adjustment of global gridded precipitation for systematic bias. *Journal of Geophysical Research: Atmospheres*, 108(D9), 2003. doi:10.1029/2002JD002499.

[2] Jennifer C. Adam, Elizabeth A. Clark, Dennis P. Lettenmaier, and Eric F. Wood. Correction of global precipitation products for orographic effects. *Journal of Climate*, 19(1):15–38, 2006. doi:10.1175/JCLI3604.1.