<u>Replies to reviews</u>

"Revisiting parameter sensitivities in the Variable Infiltration Capacity model across a hydroclimatic gradient"

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We thank the Editor and the reviewers for their time in commenting on our paper. We provide responses to each individual point below. For clarity, comments are given in italics, and our responses are given in plain blue text.

Anonymous Referee #1

This paper studies the sensitivity of the VIC model to 43 soil, vegetation, and snow parameters using the DELSA sensitivity analysis method in about 5500, 0.05 degree grid cells in Chile. The authors find that different goodness-of-fit metrics (the authors try eight of these) have more or less sensitivity to different parameters. Precipitation and aridity are also found to control parameter sensitivity. Recommendations are provided for how to select calibration parameters based on climatology and which variable is of interest.

Summary of findings:

- *VIC is overparameterized - only 12 of the 43 parameters are sensitive – 7 soil parameters, 2 vegetation parameters, and 3 snow parameters.*
- *Mean annual precipitation and aridity control which parameters are sensitive.*
- *Leaf area index and hard-coded snow parameters are sensitive.*
- *Provides guidance on the most relevant parameters for model calibration depending on the target process (runoff, snow, or ET) and climate type (humid/arid).*

This paper is well-written, and I think it will be a useful resource for VIC modelers, as it describes the VIC parameters in depth, where they came from, and what good min/max values are for calibration. Its point that some of the hard-coded snow model parameters are sensitive and perhaps should be exposed to users is well-taken.

We thank the reviewer for his/her positive feedback.

My main criticism of this paper is that some of the findings, e.g. that VIC is overparameterized and certain parameters are more sensitive under certain conditions – are well-known from other studies (such as Demaria et al., 2007 and Gou et al., 2020).

We agree that our study confirms that VIC is overparameterized, and that relative sensitivities vary depending on the specific metrics analysed. Nevertheless, our results are not directly comparable to the studies mentioned by the reviewer, since Demaria et al. (2007) and Gou et al. (2020) only included soil parameters – 7 and 15, respectively – in their analyses, ignoring the potential effects that a large number of vegetation parameters and hard-coded snow parameters exert on simulated hydrological responses.

More generally, the results and conclusions reported in this paper are not directly comparable to any study listed in Table 1, due to differences in the experimental design

and domains of interest. In particular, our study considers (1) a large number of soil, vegetation and snow parameters – only comparable to Bennett et al. (2018), who included 46 parameters (though excluding snow) –, (2) a larger number of process-oriented metrics (compared to the previous efforts listed in Table 1), and (3) a very large sample of grid cells at a relatively high (~5 km) horizontal resolution, spanning very different physiographic characteristics and hydroclimatic conditions. Hence, our study contributes to the existing literature by providing guidance on relevant VIC parameters for a suite of target processes and climate types. We have strengthened these points by adding the following paragraph in section 5 (L450-459):

"This study reaffirms overparameterization issues in the VIC model (Demaria et al., 2007; Gou et al., 2020), and that relative parameter importance varies depending on the specific metric or variable analysed (Chaney et al., 2015; Bennett et al., 2018; Yeste et al., 2020; Melsen & Guse, 2021), and physiographic or climatic site characteristics (Liang & Guo, 2003; Demaria et al., 2007; Lilhare et al., 2020). However, the results and conclusions reported here are not directly comparable to previous studies due to differences in the experimental designs and domains of interest. In particular, our study considers (1) a large number of soil, vegetation and snow parameters – only comparable to Bennett et al. (2018), who included 46 parameters (excluding snow processes) over the semiarid Colorado River basin –, (2) a larger number of process-oriented metrics (compared previous efforts listed in Table 1), and (3) a very large sample of grid cells at a relatively high (~5 km) horizontal resolution, spanning very different physiographic characteristics and hydroclimatic conditions. Hence, our study contributes to the existing literature by providing guidance on relevant VIC parameters for a suite of target processes and climate types."

On the other hand, examining parameter interactions, which the authors say is possible using the DELSA method, might be more interesting.

In this paper, we used the same DELSA formulation proposed in the original paper (Rakovec et al., 2014), which does not enable the quantification of parameter interactions. The latter would require mathematical developments that are out of the scope of this paper. We have re-worded the text to clarify this (L191-194):

"Although DELSA only examines first-order sensitivities, it has unexplored potential to be expanded with the aim to quantify parameter interactions (Zegers et al., 2020), which could be achieved by including additional terms in the local total variance (Sobol' & Kucherenko, 2010)."

Some other critiques:

1) *I wonder whether the amount of peak SWE is a useful goodness-of-fit parameter. I imagine that many combinations of parameters could give the same peak SWE, since it is an integrated measure of the entire season's snowfall. This would be worth mentioning in Section 3.4 performance metrics.*

Characterising parameter equifinality, which also occurs in other metrics, is beyond the scope of this study. Nevertheless, we clarify what peak SWE represents following the reviewer's suggestion (L234-236):

"We use two metrics to characterize snow cover processes: the difference in long-term simulated peak SWE – an integrated measure of processes occurring during the snowfall season –, and the difference in snow cover duration, quantified by the number of days with snow on the ground (Mizukami et al., 2014)."

2) *You study 101 catchments throughout Chile, but only a few catchments are highlighted in the figures. Is there any justification for why these catchments are spotlighted?*

We highlight a small sample of six basins in Figures 1-3 because they have different aridity indices and seasonal cycles of rainfall, snowfall, runoff and temperature, illustrating the diversity of hydroclimate regimes across the country. These catchments exemplify the transition from an arid, rainfall dominated regime (Far North), to semi-arid, snow-dominated basins, towards mixed and rainfall dominated streamflow regimes with lower aridity indices in southern Chile (as described in L120-124).

We have added the following text to clarify the motivation of highlighting a small sample of six basins (L118-120):

"Figure 2 illustrates this by showing the aridity indices and seasonal cycles of rainfall, snowfall, runoff and temperature for a sample of six basins with very different hydroclimatic regimes."

3) *In Figure 3, indicate whether the rows are organized by latitude (they appear to be, but it would help readers interpret the figure if this were more clear).*

We have included "(displayed in different rows, sorted by latitude)", following the reviewer's recommendation.

4) *L315: SnowLegth typo*

Thanks for noting this. We have corrected the typo accordingly.

5) *In Section 4.3.1, it is claimed that humid environments enable recharge of the lower soil layers and thus cause increased sensitivity of baseflow parameters. Is this true for all wet catchments, or does it depend whether precipitation occurs as rainfall or snowfall? I imagine that snowy catchments will have more sensitivity to baseflow parameters, as water will have more time to infiltrate into the soils. (I'm assuming here that snowmelt runoff is generated more gradually than rainfall runoff.)*

We thank the reviewer for this insightful observation. The climatic classification of grid cells used here – spanning from humid to hyper-arid – is solely based on the mean annual aridity index (Table 5) and, therefore, humid grid cells include both rainfall and snowfall dominated climates. To test the reviewer's hypothesis, we computed the fraction of precipitation falling as snowfall (f_s) in the 2,189 grid cells classified as 'humid', defining the modeling units where $f_s \geq 0.15$ as snowfall-dominated

(Berghuijs et al., 2014). We estimate f_s with the 3-hourly meteorological time series used to compute parameter sensitivities (April/2001 – March/2011), using a temperature threshold of 1 °C for partitioning precipitation between rainfall and snowfall (Hock, 2003). As a result, we find that 711 (32.5%) humid grid cells are snowfall dominated, and the remaining 1,478 cells (67.5%) are rainfall dominated.

The stratification of parameter sensitivities in humid grid cells based on the dominant precipitation phase reveals that the three most important parameters in rainfall dominated grid cells remain the same for all metrics. In snowfall dominated grid cells, the ranking of relevant parameters is the same for all metrics, excepting RMSE and TRMSE (Table 1), for which ALB THA arises as the most important parameter. Such behavior is expected because ALB THA affects snow albedo during melting periods; nevertheless, the baseflow parameters Ds Max and Ds are still important in humid, snowfall dominated grid cells, with IS_L medians that are similar to those obtained from all humid grid cells. Therefore, we conclude that baseflow parameters provide important sensitivities across humid grid cells, regardless of the dominant precipitation phase.

We have included the following text in section 4.3.1 to make this point (L390-392): "Interestingly, in humid subdomains baseflow parameters yield high sensitivities in both rainfall and snowfall dominated grid cells, although ALB THA emerges as the most important parameter for RMSE and TRMSE in snowfall dominated grid cells (not shown)."

Table 1: List with the three most sensitive parameters for all humid grid cells (same as in Table 6), and for snowfall dominated humid grid cells

Metric	All humid grid cells (n = 2,189; same as in Table 6)		Snowfall dominated humid grid cells (n = 711)	
	Parameter	IS_l median	Parameter	IS_l median
RMSE	Ds Max	0.16	ALB THA	0.211
	Ws	0.129	Ds Max	0.163
	Depth 3	0.109	Ws	0.133
TRMSE	Ds Max	0.152	ALB THA	0.202
	Ws	0.11	Ds Max	0.159
	Ds	0.104	Ws	0.118

6) L380: syntax should be "LAI, Rmin, etc. being the most important parameters."

Thanks for noting this. We have corrected the syntax following the reviewer's recommendation.

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