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## Comment on gmd-2021-92

Anonymous Referee #2

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Referee comment on "Snow Multidata Mapping and Modeling (S3M) 5.1: a distributed cryospheric model with dry and wet snow, data assimilation, glacier mass balance, and debris-driven melt" by Francesco Avanzi et al., Geosci. Model Dev. Discuss., <https://doi.org/10.5194/gmd-2021-92-RC2>, 2021

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In "S3M 5.1: a distributed cryospheric model with dry and wet snow, data assimilation, glacier mass balance, and debris-driven melt" the authors present a distributed cryosphere model to aid in flood forecasting. This is well written and generally easy to follow with a few portions unclear, somewhat due to the manuscript length.

My main criticism is regarding how the model's process representations and how they are presented. In the abstract the authors note that "Model physics include precipitation-phase partitioning, snow and glacier energy and mass balances, snow rheology and hydraulics, and a data-assimilation protocol." This led me to believe I would be reading a paper about an energy balance model, however this is not at all the case. Indeed the model is a basic temperature-index snow model with a radiation component. There are no internal snowpack energetics, no longwave losses, no turbulent heat fluxes, and no sublimation. Nor is there a vegetation canopy parameterization. Large portions of the study area (c.f. Figure 8) appears to have vegetation cover, so I am at a loss as to how this interaction can be ignored. These are critical components that have been identified by snow hydrologists for many years.

Certainly this criticism could be waved away as a differing in model philosophy, however the results have issues that suggest there is something quite wrong with these simplifications as applied. In Figure 6 there are multiple years (2013, 2014, 2015, 2016) and sometimes multiple occurrences per year, where 1m to 2m snowpacks are almost instantly ablated. I don't understand the physical process by which this could occur. Rain on snow run a-muck? A warm, sunny day "melting" a deep snowpack that has no cold content tracked? I understood these results to be with the data assimilation turned on (this was a bit unclear to me). Assuming this is true, then without the data assimilation system these results would have been even more wrong. The DA is then massively compensating for broken parameterizations. If this was without DA, then how is it ablating a 1m snow pack, then immediately reestablishing a 1m snowpack? A similar situation occurs on the glacier, where 2x melt is predicted or the case of Petit Graphillon where multiple meters of ablation are observed with no reaction of the model. Considering this

model is described as a flood forecasting model, I am concerned with the non-physical behaviour that is being exhibited here.

I understand that the authors address some of these issues as 'future work', such as the canopy. However, these processes are so critical for basin hydrology that, to present a model to tie into a hydrology model without key cold-region processes, seems unfinished and incomplete. I also don't agree with the framing that t-index parameterizations are a high degree of physical realism, especially when so many other critical processes are omitted. Lastly, I am surprised by the authors stating that coupling radiation to a temperature index model is novel. Hock (2003) details approaches that include this idea and more recent examples exist, e.g., Follum et al (2015).

Hock, R. Temperature index melt modelling in mountain areas. *Water Resources Research* **282**, 104 115 (2003).

Follum, M. L., Downer, C. W., Niemann, J. D., Roylance, S. M. & Vuyovich, C. M. A radiation-derived temperature-index snow routine for the GSSHA hydrologic model. *J Hydrol* **529**, 723–736 (2015).

Specific comment in format of

L<ine> [0-9]+ "quoted text"

Comment under

Page 1

L4 a high degree of physical realism

Do you mean they are mostly empirical? Certainly many models have good physical representations. Indeed I'd expect most models that simulate physical processes to have physical realism!

L7 reconstructs

Simulates?

L16 the paper comprises an user manual

I would like to see an actual science question. In my opinion, even in GMD, there should be some hypothesis testing and scientific questions answered that support model development.

Page 2

L22 during the warm, summer season

And spring

L22 when demand

By whom?

L25 while 1.4+ billion people in Asia rely on discharge from high-mountain

Citation?

L33 large portfolio

W/c

L36 avalanche forecasting

perhaps "Avalanche hazard forecast"

L36 so weather

?

L37 aridity

AR6 suggests location dependent, consider citing the newest IPCC report

L42 Regarding seasonal snow

Suggest adding FSM (Essery, 2015) to this list.

Page 3

L60 The evidence that simplified and complex models often yield comparable predictive

Certainly many models exist that show better SWE and sd when including full physics e.g Lafaysse (2017) and Vionnet (2021)

A multiphysical ensemble system of numerical snow modelling, Lafaysse, et al (2017) The Cryosphere

Multi-scale snowdrift-permitting modelling of mountain snowpack, Vionnet et al, The Cryosphere 2021

Even when considering just SWE and SD, the inclusion of multi-layer snowpack models is important for deep mountain snow covers, or rain on snow events.

L 63 low complexity when it comes to internal layering and micro-scale properties

Ok but what about the other processes that impact?

L65 real-world

L67 these four factors trace back

As written this suggests obs are related to empiricism, and I don't understand how Obs location biases are due to empiricism.

L71 all the four factors

Seems like factors is used as "requirement" which is not true.

L72 parsimonious as for

Suggest this isn't a requirement

L75 and so

?

L75 avalanche forecasting

Without the microstructure is this really true?

L81 Section 3 presents an example of results for an inner alpine valley

Ok great! I would like to see a science question. Even GMD should have-science questions and hypothesis testing

Page 4

L86 being

L86 no spatial interdependency

I read this to mean no lateral mass or energy transfer? Perhaps be explicit

L90 using a forward-Euler method.

This is a basic solver, why this method versus the RK, BE, etc methods? What tolerances were used? I assume a constant step size?

L106 The density of glacier ice is assumed equal to  $\rho_i$ .

So no further compression?

Page 5

L123 state variable

Some of these look like fluxes e.g  $M_G$ . The SWE etc looks to be a diagnostic variable and the ice lattice is the actual state variable. Later in the manuscript SWE is noted as a diagnostic variable. I would suggest tidying this up and making the diagram clear.

L123 inputs

Unclear what is an input: is an albedo input?

L128 where  $S^{\wedge}$

What do the hats denote? I don't think it is noted explicitly in the text

L129 and  $O^{\wedge}$  is the outflow mass flux

Above you call this a state in figure 1

Page 6

Figure 1: Main definitions,

Add units, see above note on fluxes/state

Page 7

L145 S W ED and S W EW

Are these not diagnostic?

Page 8

L169 is standard in degree-day model

From the intro I was not expecting this to be yet another temperature index model

L176 seems yielding satisfactory results

Grammar

L176 especially in suppressing mid-winter melt episodes that do not appear in validation data.

Mid winter melt will increase with climate warming though. Further, your results show non-physical mid winter ablation events. Lastly this appears to be an ad hoc calibration, is that true?

L177 decoupling radiative forcing

I mean, this is the point of a full energy balance model

L181 where  $S_r$  is incoming shortwave

This section needs units. I see the below section has it, please put these into the above text

L184 sets  $S_r$  to 0 between 7PM and 7AM according to forcing timestamps

This seems arbitrary. Why not just compute load sun rise and set?

Page 9

L195 otherwise.

Move to start of statement

L197 (timestamp time)

Whit does this mean?

L200 sensitivity of S3M to both is rather low.

Based on?

L201 closer to physics

What does this mean? Do you mean closer to a fully first-principals energy balance model?

L202 this hybrid approach

There are tons of temp+rad formulations. Either this isn't new or the contribution is not clear me to me

L 206 Which is an isothermal, very efficient condition for shortwave radiation to convert into actual melt.

Awkward, suggest clarify

L208 regardless of the actual cold content.

Is the case the authors making that their contribution is a cold content temp index? Cold content is /required/ to correctly track energetics in deep mountain snowcovers

L 210 To mimic this transition

This is what the cold content tracking should do, sn't it? It is not clear to me how this

approach works with deep mountain snowcovers.

Page 10

L229 Refreezing is computed

Does this refreezing latent heat flux decrease the cold content ie warm snowpack?

L230 eq 19, R

Remind the reader what "R" is please

Page 12

L269 Report instabilities of Equation 20

Could this be due to using FE? And to be clear, this is the use of 20 that is a problem and not the solution to 20?

L 269 high saturation value

So numerics are likely a problem?

L269 very shallow snowpack

This is classically a tough problem and requires a good eb model + good numerical scheme

L 276 a representative element at 66% depth:

Where does 66% come from? This seems arbitrary

Page 13

L290 While it is set to 0°C otherwise.

So a 2m mountain snow cover is set to instantly isothermal?

Perhaps I am misreading this, but it seems to me that the authors are suggesting that as soon as  $T_{air} > 0$ , they set the ground temperature to be  $= T_{air}$ ? If that's what is happening, then that is completely wrong, especially for deep mountain snow covers. If that isn't what is happening, then please clarify this, as despite reading it a few times I am still uncertain on what, exactly, is being done.

L293 thus implying that refreezing has no impact on snow structure

So, what is the point then? Latent heat and Cold Content tracking? I am picking on this specifically due to the noting of avalanche hazard forecasting in the introduction

Section 3.5 Data assimilation

This is direct insertion, correct? I understand the authors not wanting to cut and paste verbatim from existing papers, and I appreciate them keeping the length of this manuscript down. However I did struggle through this section to know, exactly, how this was done. Specifically that  $S_{we}$  and  $S_d$  are diagnostic variables, but seem to be assimilated as a state variable

Page 14

L 307 of Updating

Fix cap

Page 15

L347 total SWE in S3M v5.1 is only a diagnostic variable

As noted above this needs to be fixed in figure 1 and the text throughout for consistency

L347 S3M also supports assimilating only positive differences in Equation 36, that is, only correcting modeled SWE if observations are larger than simulations

I am a bit surprised by this tactic. Certainly it helps recover from the otherwise catastrophic mid winter melts, but doesn't help with over estimates in SWE/SD. I'd like to see a bit more elaboration as to why it is done this way

Page 16

L376 equivalent to G1

Maybe section 2.4.1 would benefit from text that notes what  $g_1$  is as I got here and was confused.  $G_1$  is only used in the heading. Would be maybe nice to remind the reader what this is.

Page 17

L 391 any residual SWE at the end of each water year is added to  $h_G$

Ok so this ignores firn then. In multi-year firn processes I'm skeptical this can be ignored, but I understand that in some Alps glaciers this approximation can be valid. I would like to see supporting literature for this assumption.

L 398 parametrizing

Spelling

Page 18

L 446 spatialize and downscale weather-input data,

Aren't these data already spatial datasets? So is this just a downscale to the numerical model grid? Please note the methods used to do so (eg what spatial interpolant/regridding is being used) [ ah, I see there is a note in the appendix on this, perhaps either reduce the text and move it into the main body or explicitly note the appendix section].

L 448 using the Continuum model

What is this?

Page 20

L470 the notions that

This is unclear to me what you mean by notions here. Do you mean 'notion'? 100% seems very high

L470 of transmitted shortwave radiation

Transmitted through what? No reflectance?

L476 mainly for computational-resource constraints.

Less brute force methods can be quite efficient. E.g.,

Saman Razavi, Razi Sheikholeslami, Hoshin V. Gupta, Amin Haghnegahdar, VARS-TOOL: A toolbox for comprehensive, efficient, and robust sensitivity and uncertainty analysis,

Environmental Modelling & Software, Volume 112, 2019,

L486 , in line with expectations

L489 that the sensitivity of S3M to  $m'$ rad and  $mr$  is surprisingly low

Doesn't this go against what was previously stated? If this is the case though, then what is causing the huge mid winter ablation events?

Page 21

3.2 Evaluation: point snow depth

Should note this has assimilation in it is my thinking was that this was sans assimilation like the previous section.

L 498 Sections

Page 23

3.3 Evaluation: the Torgnon study plot

This is with assimilation right? I'm not totally sure why but I'm struggling to remember which runs have assimilation and which do not.

L519 (Figure 6)

What is going on with the mid winter ablation events? It seems assimilation is heavily compensating for these impacts?

L536 not reported for brevity

L536 qualitatively

Wouldn't this be quantitatively?

Page 27

L562 provides renovated

Not sure what this means. W/c

L566 S3M is among the first parsimonious snow models to provide such information.

I don't accept that temp index models can work when applied to climate change forecasts. The loss of stationarity eg Milly(2008) leads to huge challenges in applying hindcast calibrated models to future conditions. For example, the increase in mid winter ablation makes calibrated models that assume a spring melt (and implicitly calibrate for the deep snowpacks) will likely fail when applied to very different types of winters.

Milly 2008, Stationarity Is Dead: Whither Water Management?

L 576 solid results

Word choice

L580 and the Petit Grapillon,

These results seem really poor if observations show 2m of ablation but 0m is predicted!

Page 29

L600 at a comparatively high standard in physical realism.

A temperature index snowmelt model with no: canopy interactions, sublimation, blowing snow, energy balance, etc. I am not convinced this is a high amount of physical realism.

Page 30

L610 to produce future scenarios of

See my previous comment on applying calibrated tindex models to future climates.

L613 for an ordinary laptop

What does this mean? Please give a sense of CPU arch, speeds, etc. As a model design philosophy, I am not so sure that constraining the physics and conceptualization so-as to run on a laptop is optimal.

L616 the scarcity of open- source suites reconnecting them with the hydrologic cycl

I don't I understand this comment

Page 32

L658 energy and mass balances,

Temperature index models are not an energy balance.

L679 I've never seen a license agreement in a code availability section. Not saying it is

wrong, but I personally think it should be removed, indeed the code itself should have the license agreement in it.

L715I see that this is where the input data requirements are. I think this should be referred to explicitly from the main text

L751 I was not able to get this to compile on MacOS due to a unlimit being specified in the .sh