Hydrol. Earth Syst. Sci. Discuss.,
doi:10.5194/hess-2016-272-AC2, 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Interactive comment on "Bridging glacier and river catchment scales: an efficient representation of glacier dynamics in a hydrological model" *by* Michel Wortmann et al.

Michel Wortmann et al.

wortmann@pik-potsdam.de

Received and published: 7 October 2016

Thank you for the review and constructive comments. We have responded point by point below with your comments in italic.

General assessment: This manuscript introduces a distributed catchment model that incorporates a representation of glacier dynamics. The spatial representation within the model lies midway between semi-distributed models, which represent spatial variability using grouped response units (GRUs), and fully distributed models such as the grid-based DHSVM. The goal is to retain the physical realism attainable through the fully distributed approach while maintaining the computational efficiency of GRU-based models. If successful, such a model would be a valuable tool for making projections of

future streamflow variability. Therefore, the topic of the manuscript is highly relevant to the readership of HESS. However, there are a number of points that require attention before the manuscript could be accepted for publication. In particular, a number of the process representations appear ad-hoc, poorly constrained and/or physically unrealistic.

Thank you for both criticism and praise. We have tried to clarify the process descriptions and emphasise the need for relatively simple but robust formulations in the face of data scarcity. Parsimonious process descriptions (unfortunately) often rely on empirical parameters that must be chosen wisely based on available literature sources. This was our choice for the glacio-hydrological model in hand, which tries to balance physical process descriptions and data availability. In addition, we have illustrated the sensitivity of the individual parameters included in the glacier module in a sensitivity analysis (included in supplementary material). Answers to specific comments are given below.

1. The authors model ice height, which requires an initial estimate of the elevation of the ice bed, which is made using the Glabtop2 approach. How sensitive are the modelled glacier dynamics to uncertainties in the initial elevation estimates?

The model does not need an initial estimate of the ice bed, instead we are using the Glabtop2 simulations to calibrate ice thickness via the rheology term χ in Eq. 2. The average error of Glabtop2 was shown to be 7% in larger glacierised regions (Frey et al., 2014), which is negligible given the uncertainties of the catchment-wide thickness calibration using a global shear stress in our model.

2. Further to the preceding point, elevations of the glacier hydrotopes would vary through time as the glacier geometry evolves. Is this accounted for in the model – e.g., for air temperature calculation?

No this is not accounted for because the glacier thickness will not decrease below the critical height. The glacier area is reduced when the unit melts further as illustrated in

Fig. 2. While accounting for it would be possible, it would only have a limited impact for the above reason. Also, the model set up would rely on the externally modelled thickness, e.g. from Glabtop2, which is both error-prone and may not always be available.

3. p. 2 line 34 to p. 3 line 2. Include example reference(s) for greater specificity on this point – perhaps Jost et al. (2012) HESS 16: 849-860.

Thank you, we included it.

4. Equation 3 seems ad hoc. Is there an empirical or theoretical basis for it? How sensitive is the model to this specific formulation?

Since the shape of the glacier units is unknown, the initial formulation assumes that they are rectangular blocks where the width is approximated by the squareroot of the area. Referee #3 has suggested the slightly more realistic formulation of a wedge-shaped front, relying on the same assumption for the width. It is now included in section 2.4.

5. Is there any way to validate the avalanche routine? How sensitive are model predictions to leaving it out?

Validation is difficult but observed glacier outlines above the ELA give an indication of critical slope angles, but steep, high elevation terrain is also prone to misclassification in glacier outlines. Leaving it out would prevent adjusting the glacier hypsometry above the ELA to observations and also reduce snow accumulation.

6. Section 2.6. Is the melt factor for glacier ice enhanced relative to the melt factor for snow?

No, the melt factors for snow and ice are calibrated separately but the snow melt factor is also scaled by the sun hours to account for aspect and terrain shading.

7. Section 2.6. Is the residence time constant? Many empirical and modelling studies have demonstrated a seasonal variation, especially in relation to the timing of snow

disappearance.

The residence time is constant mainly to avoid parameter redundancy of a parameter that is not very sensitive at the catchment scale and the daily time step (this has been checked). It is, however, included as a single parameter to account for the delays between melt and runoff, where it is important, e.g. in smaller catchments.

8. Section 2.6. Glacier outflow is subject to infiltration into a soil layer and surface runoff when that layer saturates. This does not seem realistic. Much, if not most, glacier outflow occurs via subglacial channel networks that evolve through the melt season.

Thanks! Yes, this is correct and most discharge is generated by 'surface runoff' because the thin (30-100cm) subglacial soil/sediment layer is saturated throughout the melting season. However, the process of evolving channel networks is not included as it has little influence on discharge at the catchment scale.

9. Section 2.6. Water is lost from glacier storage by evaporation at a rate determined by the Priestley-Taylor (P-T) equation (note spelling). However, the available energy term in standard applications of the P-T equation would not be appropriate for a glacier. Many express the available energy as Rn-G (Rn = net radiation, G = ground heat flux), which would be better expressed as Rn-M (M = energy consumption by melt) for a glacier. Some applications of the P-T equation leave out the ground heat flux (approximately justified for daily time steps on the basis that the net ground heat flux would be negligible). This approach would also not be appropriate for a glacier. How does the SWIM model represent the P-T equation?

The P-T equation is the standard method of SWIM to estimate potential evapotranspiration, which was adopted for lack of appropriate equations for ice surfaces without solving the full energy balance at the glacier surface. We instead assume that melt water left in the linear reservoir is available for free surface evaporation (water saturated firn, supraglacial puddles, ponds and lakes), which is reasonable given the data constraints.

10. Section 2.6. For calculating E using the P-T equation, is the air temperature adjusted to account for conditions within the glacier boundary layer? See papers by Ayala et al. (2015, JGR-Atmos. 3139-3157, DOI: 10.1002/2015JD023137) and references cited therein on the variations of temperature and humidity over a glacier relative to off-glacier measurements.

Given the scope of the model for data-scarce catchments, this process is difficult to represent at the large catchment scale with gridded temperature data. We also do not consider glacier flow lines because they are mostly only available for large valley glaciers.

11. Equations 5 and 14. Are these derivatives or finite differences? If the former, use d_/d_ as the operator; if the latter, use upper-case delta for lack of ambiguity. What numerical scheme is used to solve the equations?

These are simple first order difference equations, we corrected the equations accordingly with capital delta over time step d (day).

12. Equation 7. "E" has previously been used for evaporation. Use a different symbol.

Thank you, evaporation is renamed to EP.

13. Equation 7. Hydrologists and climatologists commonly use beta for the Bowen ratio. Consider using a different symbol to avoid confusion.

Thank you, we changed it to Γ.

14. Equation 7. Is a temporally and spatially constant sublimation ratio physically realistic? Can the authors draw upon work on sublimation in the dry Andes, for example, to support their parameterization?

See below answer on questions 14 and 15.

15. Equation 7. It seems redundant to compute both evaporation and sublimation at each time step. Evaporation would occur from a melting surface for which a water film covers ice or snow grains. Sublimation would occur from a non-melting surface lacking a water film.

Thanks for these comments! While sublimation ratios most definitely vary significantly over a catchment area and time, the factors (shortwave radiation, latent heat flux, wind speed, roughness etc. as found on low-latitude glaciers) to determine time and space varying sublimation are not readily available at the catchment scale. We thus rely on the findings of point observations (eg. Winkler et al. 2009; Zhang et al., 2012; MÃÂűlg et al. 2009) and theoretical considerations to at least include sublimation as a first order estimation over the entire catchment and considering annual mass balances only. In our opinion, this is justified given the relative importance of sublimation.

16. p. 8 line 1. Slope and aspect enhance insolation on equator-facing aspects, not just reduce it.

Thanks, we corrected to 'alter' instead. The enhancing effect is considered through sunshine hours greater than 12 on a given day.

17. Equation 14. What are the units of C?

C is the concentration or fraction of debris in the ice column and is thus dimensionless (added to section 2.9).

18. I have trouble understanding Equation 14. Shouldn't there be lateral flux terms (Q_i in Equation 2) to represent fluxes of sediment from the up-gradient unit and to the down-gradient unit?

We have corrected the equation to be a valid first order difference equation describing the change in concentration over one day (as in the model code). We changed melt to ablation to also consider sublimation. The equation is now better described in section 2.9: The first term changes the concentration according to the ratio of the specific mass balance ($A - H_s$). The second term describes the 'dilution' of the ice flux from the upstream unit ($C_u - C_g$).

19. I may have missed it, but I could not find which years were used for calibration and which for validation. For example, are the time series shown in Figure 4 for the calibration or validation period?

Thanks for pointing that out, we have added these periods to section 2.12 and table 3. For the Rhone catchment: calibration period 1980–1995, validation period 1996–2010. For the Aksu catchment: calibration period 1971–1978/1982 (Xiehela/Sary Djaz), validation period 1978/1982–1987/1996.

Editorial comments 1. Use the past tense when referring to previous studies. 2. There are a number of minor editorial corrections to be made. Some examples are provided below. 3. p. 7 line 28. Zhao et al. and Winkler et al. are not in the reference list. 4. p. 8 line 7. "sinus" should be "sine" 5. p. 8 line 13. "defuse" should be "diffuse" 6. p. 8 line 7. Use a colon rather than a semi-colon here. 7. p. 11 line 20. Nash-Sutcliffe misspelled 8. p. 11 line 27. ...at least one objective...(?) 9. p. 12 line 28. "complimented" should be "complemented"

Thank you for pointing out these editorial changes, they have all been integrated.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-272/hess-2016-272-AC2-supplement.pdf

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-272, 2016.