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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Temperature signal in suspended sediment export from an Alpine catchment" *by* Anna Costa et al.

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We thank Referee #2 for his/her review. We consider that the comments on snow (comment "Section 3.1, snow model") and ice model (comment "Ice model") are the most important. Therefore, we discuss here these two points, while other comments on goals, structure, and more detailed suggestions will be implemented in the revised manuscript. To address the concerns of the Referee about the ice-melt component of our work, we performed additional analyses and outline the results here. This discussion and results will also be reproduced in the revised manuscript.

1- Referee's Comment on Section 3.1, snow model: Several parameters that play an important role in the degree day approach (as SD, Trs, Tsm) are set before calibration. A sensitivity analysis of the impacts of these parameters would be interesting to assess

their impact on the results and give them more credit.

1- Authors Reply on Section 3.1, snow model: We agree with Referee #2 that it would be interesting to estimate the impact of parameters on the snow model results. Therefore, we will perform a sensitivity analysis on TRS, TSM and Ksnow as the key parameters of the snow model. We will also assume different snow depth thresholds for considering what is a snow covered surface. Results will be included in the revised manuscript.

2- Referee's Comment on Ice model: In my opinion the most critical point of the method is the simplicity of the ice melt simulation. The ice model uses a simple degree day routine and do not considers changes in glacier areas, which might be consequent over a time period of ca 50 years. The authors claim "Temporal dynamics of glacier coverage are not accounted for âĂŤ- ice accumulation, glacier retreat and ice movement are disregarded. The reduction of Alpine glaciers for the period 1950–2000 was estimated to be within the 10 range 500– 1000 m (Hoelzle, 2003; Oerlemans, 2005), while our effective climate grid resolution is 2_2 km, i.e. the retreat is considerably lower than the grid resolution of climatic inputs. The consideration of ice dynamics would therefore add a degree of complexity that our spatial resolution cannot take advantage of" (p. 11, l. 8-12). I disagree with this argumentation. The grid size of the meteorological product is surely important for the modelling of glacier retreat, but many studies used these meteorological dataset for modelling changes in glacier mass balance in the Alps and proved that the results were accurate enough. The model resolution for the ice melt calculation is 250 m and is therefore "small" enough to be influenced by a glacier retreat in range of 500-1000 m. My concern is that if the glacier retreat is not taken into account in the modelling of such a long period (50 years, with very high rates of glacier retreat in the last decade), there is a real risk of overestimating the glacier melt by the model. The results of the analysis suggest that there is a shift in the discharge from a snow-melt dominated regime to an ice-melt dominated regime (Fig. 10 and 12). I wonder if part of this increase in ice-melt can be induced by the fact that glacier retreat is not taken into account. Therefore I would suggest the authors to discuss in more details the impact of this model assumption on the results. Many glaciers in the Rhone basin are well documented and have yearly mass balance data. It would be worth to compare the modeled ice melt values with measured time series of glacier mass balance to exclude that the increase of ice melt is due to model assumptions.

2- Authors Reply on Ice model: This is indeed a very important point, and we agree with Referee #2 that neglecting glacier dynamics may influence the estimation of ice-melt rates. The Referee raises the possibility that by neglecting glacier volume loss (retreat) we are possibly overestimating the ice-melt contribution over our study period. To provide evidence that this is not the case, we compared our simulations with time series produced with the Global Glacier Evolution Model (GloGEM), a model accounting both for the main mass balance components and glacier dynamics. For comparison, we used total monthly runoff (snowmelt + ice-melt + rainfall) generated at the glaciated surfaces of the upper Rhone basin, simulated with GloGEM (Huss and Hock, 2015) for the period 1980-2010.

GloGEM computes the mass balance for every 10-m elevation band of each glacier, by estimating snow accumulation, snow and ice melt, and refreezing of rain and melt water. The response of glaciers to changes in mass balance is modelled on the basis of an empirical equation between ice thickness changes and normalized elevation range parametrized as proposed by Huss (Huss et al., 2010). Normalized surface elevation changes Δhr are derived for each elevation band from mass balance changes (mass conservation). Starting from initial values derived by the method of Huss and Farinotti (2012), ice thickness is updated at the end of each hydrological year by applying the relation between normalized elevation range hr and normalized surface elevation change Δhr. The area of each glacier is finally adjusted by a parabolic cross-sectional shape of the glacier bed (Huss and Hock, 2015). GloGEM is calibrated and validated over the period 1980-2010 with estimates of glacier mass changes by Gardner et al. (2013) and in situ measurements provided by the World Glacier Monitoring Service.

Although in our hydrological model, which considers precipitation, snowmelt, ice-melt at pixel scale, but integrates them to basin-average values, we do not include glacier dynamics, the total annual volumes of runoff (snowmelt + ice-melt + rainfall) from glaciated areas, correlate very well with results of GloGEM (Fig. 1a). Measures of performance confirm the agreement between the two models: the correlation coefficient is equal to 0.86 and the Nash-Sutcliffe efficiency is equal to 0.67. We are also capable to capture quite well the seasonal pattern of runoff generated from glaciated areas (Fig. 1b).

Perhaps most importantly, GloGEM simulations show that total annual runoff is increasing throughout the period and there is no evidence for a drop in ice-melt rates. This confirms that, although glaciers of the upper Rhone basin are retreating, sediment-rich fluxes originated at glacial and proglacial areas are increasing during the 1980-2010 period. As expected, total runoff from glaciated surfaces and ice-melt are highly correlated (Fig. 1a). In our model, the correlation coefficient between the two variables is equal to 0.95. Therefore, the increasing tendency of total runoff simulated with GloGEM indicates that ice-melt component is most likely also rising. Non-parametric Mann-Kendall tests indicate an increasing trend with 5% significant level for total runoff and ice-melt simulated with our model and for total runoff simulated with GloGEM. Trend slopes, estimated with the Theil-Sen estimator, confirm that most likely we are not overestimating the rate of increase in ice-melt. Indeed, we find $\sim$27.65 mio m3/year and $\sim$21.71 mio m3/year, respectively for total runoff simulated with GloGEM and with our model, and only $\sim$17.90 mio m3/year for ice-melt simulated with our model. We also computed the basin-averaged mass balance accounting for snow accumulation and snow and ice-melt for each hydrological year. The mean mass balance rate over the period1980-2010 is equal to -0.78 $\pm$ 0.22 m w.e./year (Fig 2). This value is slightly greater than that found by Fischer et al. (2015) for the upper Rhone basin (-0.59 m w.e./year), but within the uncertainty of the estimate. In summary, we are confident that we can state that, although we do not account for glaciers retreat, our model results agree with a much more complex physical-based modelling approach including glacier dynamics. Both comparisons with GloGEM and our basin-averaged mass balance indicate that we are not significantly overestimating ice-melt contribution during the period 1975-2015.

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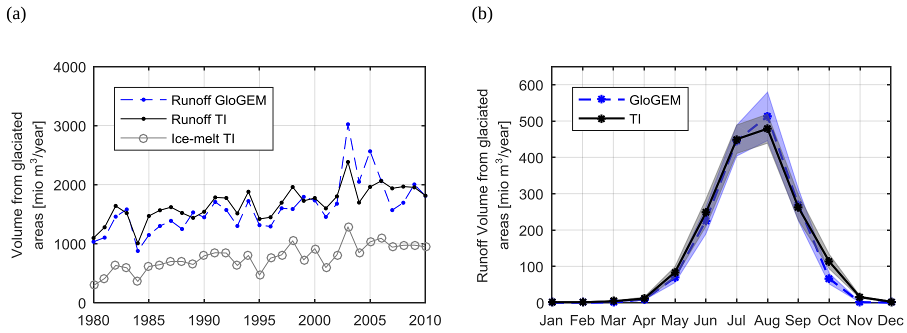

Fig. 1. Runoff (snowmelt + ice-melt + rainfall) generated at glaciated areas within the upper Rhone basin, simulated with GloGEM and with our temperature index model (TI) for the period 1980-2010: (a)

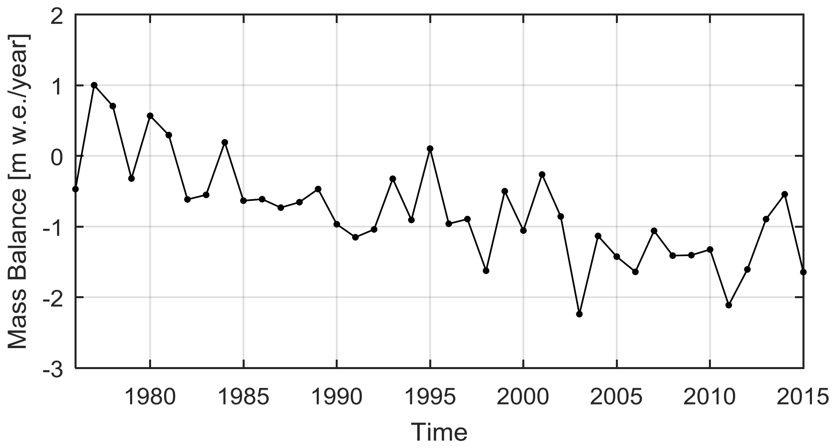

Fig. 2. Mass balance rate for glaciated areas of the upper Rhone basin, simulated with our temperature index model for the period 1975-2015.