Answer to Reviewer 3 HESS-2019-152

We thank Reviewer 3 for his insightful comments. We provide here our responses to his comments, including the plan to revise the manuscript in response to reviewer comments. The original review comments are in normal black font while our answers appear in blue font.

General Comments

This paper examined the capability of a hydrological model (GEM-Hydro) in simulating the June 2013 flood event in Alberta, Canada. In particular, three sub-basins in the Bow River basin were selected to assess the impacts of spatial resolution, precipitation gauge density, and initial snow conditions on model ability in reproducing the flow volumes. Also, the model sensitivity to Manning coefficients in capturing the peak flow was investigated.

General Comments:
The objective of this paper is straightforward and this paper is well-written, easy to follow and well-structured. However, the creditability of the study has been reduced because the study is highly localized and reads more like a report of an application of a hydrological model to a specific flood event. There are little knowledge gain for the community. In general, two major concerns are needed to be addressed in this paper:

1) Novelty of the study

While the study would be a great contribution to the development of a Canadian hydrological forecasting system, it might not be novel enough as a scientific contribution for the international community. The effects of different spatial resolutions on model simulations have been previously and heavily studied in different hydrological models and it is well expected that finer resolution could provide better simulations because of its ability in capturing the fine-scale hydro-meteorological processes. It is also expected that the inclusion of additional information (e.g. increasing network density, inclusion of SWE information) would improve model performance because of the data-driven nature of the sophisticated models nowadays. Lastly, the Manning coefficients (both channel and floodplain) are well known to be one of the most sensitive routing parameters in any hydrological/ hydraulic models. Adjusting such parameter will definitely improve the model ability in matching the peak flow timing and magnitude.

Furthermore, the Discussion section of the study did not provide innovative insights on modelling of extreme flood events. Although the Discussion section was well-written and fully supported by references, the major findings of this study were merely a confirmation of what had been shown in many previous studies (as repeatedly mentioned by the authors). Therefore, there is a lack of true novelty and scientific contribution in this study. The authors should vigorously address this critical issue by providing a better discussion on what new knowledge and information the international community could learn from this study.

We thank Reviewer 3 for this general comment. Significant changes will be made in the revised manuscript to make sure that this study bring enough novel contributions to the international community. These changes are detailed below.

First of all, some of the results that were presented in the initial manuscript will be removed since they correspond to expected results with a lack of real novelty as detailed above by Reviewer 3. We will remove from the manuscript:

- the precipitation analysis at 10 km using the default stations (*CaPA 10 km Def*). This precipitation analysis used the same stations as the operational analysis at the time of the event but its quality is mediocre due the low density of the stations in complex terrain. In the revised manuscript, we will only keep the precipitation analysis generated with all the precipitation data for each horizontal resolution (10, 2.5, 1 km). Theses different precipitation data will be presented as our best estimation of the precipitation at each horizontal resolution.

- the results corresponding to the different Manning options that were described in the section *Results*. We will describe the selection of the correction factor applied to the default values of the Manning coefficients in the section *Methods*. Indeed, as mentioned by Reviewers 2 and 3, the adjustment of the Manning coefficient does not bring novelty to our study. Therefore, we decided to present it as a calibration step. The correction factor selected at this calibration step will then be used in the rest of the analysis. Figures describing the impact of the correction factor will be added to the supplementary material of the revised manuscript. The challenges associated with the choice of the routing parameter for such extreme event will be kept in the section *Discussion*.

Removing these two components of the initial manuscript will allow us to focus the revised manuscript on the factors governing the predictions skill of extreme late-spring flood in mountainous terrain. The three **scientific questions** of the **revised manuscript** will be as follows:

1. How does the resolution of the atmospheric forcing influence the predictability of the hydrological response during extreme late-spring flood in mountainous terrain?
2. At kilometric scale, can the rain/snow partitioning from an advanced cloud microphysical scheme improve the predictability of the hydrological response during this kind of event?
3. How does the sensitivity of the hydrological response to the resolution of the atmospheric forcing and to the phase partitioning method compare to (i) the sensitivity to the initial snow conditions and (ii) the uncertainty in soil datasets?

An ensemble of hydrological simulations will be used to answer these questions:

- three atmospheric forcings will be used at 10, 2.5 and 1 km as in the initial manuscript. At each resolution, the precipitation forcing will consist of the CaPA analysis including all the stations available in the region to obtain our best estimate of precipitation at a given resolution.
- for each atmospheric forcing, the same two initial snow and soil conditions will be used as in the initial manuscript.
- finally for each atmospheric forcing and initial snow/soil conditions, two different soil database will be considered: the Global Soil Dataset for Earth System Model (GSDE, (Shangguan et al., 2014) and the Soilgrid dataset (Hengl et al., 2017). These 2 database can be considered as reference soil databases for Earth system models (Dai et al, 2019).
- for the atmospheric forcing at 1 km, for each soil dataset and initial snow conditions, three hydrological simulations will be carried out with GEM-Hydro using different phase partitioning methods (PPM): (i) a constant threshold depending on air temperature (0°C, the default value in GEM-Hydro), (ii) a more advanced PPM combining temperature and relative humidity (Harder and Pomeroy, 2013) and (iii) the direct precipitation phase from the P3 cloud microphysical model running in GEM at 1 km.

As suggested by Reviewer 3 in a specific comment below, the evaluation of the hydrological simulations will be carried out at **12 unregulated stations** located in the **headwaters** of the **Red Deer** (2 stations), **Bow** (6 stations) and **Oldman** (4 stations) River basins. Among these 12 stations, 4 stations were used in the initial manuscript. The location of these stations is given on Figure 2 below and their main characteristics are reported in Table 1 below. In total, the river basins of these 12 stations cover 12700 km^2 and are characterised by different soil characteristics, total precipitation amount during the flooding event and initial snowpack conditions prior to the flood. We strongly believe that this new set of the stations will made our analysis less localised and will allow us to derive more general conclusions useful for the international community.

For example, we will add and discuss in the revised manuscript results on the influence of the resolution of the atmospheric forcing on the simulation of the melt dynamic during the rain-on-snow event at each sub-basin where snow was initially present. Figure 1 shows that the contributions of the turbulent fluxes to the total energy input to the snowpack is larger with the atmospheric forcing at 2.5 and 1 km than at 10 km. This result is consistent across all the sub-basins and results from larger wind speed at 2.5 and 1 km than at 10 km. It illustrates that the importance of the wind field downscaling on simulated turbulent fluxes and resulting snowmelt. To our knowledge, a quantification of these effects on the hydrological response during extreme floods has never been proposed in previous studies and constitutes an original contribution of our study.

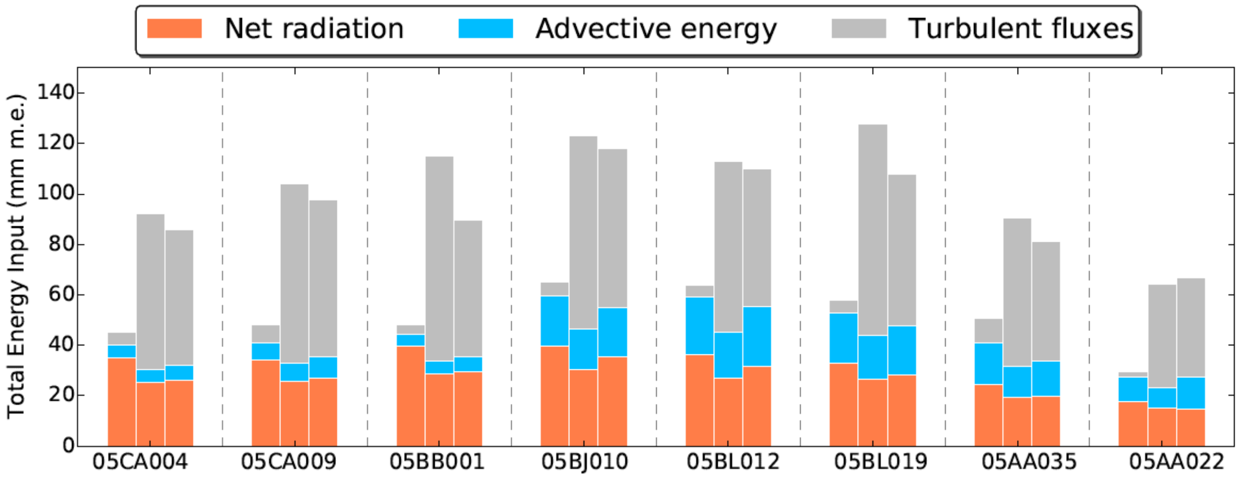

Figure 1: Contribution of energy balance terms to the total averaged energy input to the snowpack (expressed in millimetre melt equivalent) during the flooding event simulated using atmospheric forcing at different resolutions (Left: 10 km; Middle: 2.5 km; Right: 1 km) for different sub-basins. The location of the sub-basins is shown on Fig. 2 below.

Following these substantial changes, we will propose a new title for the paper: *Assessing the factors governing prediction skill of extreme late-spring flood in mountainous terrain*. The section *Discussion* of the revised manuscript will be rewritten to better highlight the scientific contribution of this study.

2) Lack of connection with other worldwide extreme flood events
The Introduction section was again well-written and the rationale of the study was well presented, however, it was highly focused on the description of the June 2013 flood event and the previous works that were related to the 2013 flooding. The literature review did not discuss any research related to other worldwide flood events and any modelling works that address the current challenges of the modelling community in dealing with extreme flood induced by rain-on-snow events. This makes the study highly localized and event specific. The authors should provide a boarder discussion on similar research conducted in other regions, modelling strategy used in simulating such kind of flood events, and the research gaps this study could fill in for advancing the knowledge of the community.

The Introduction in the revised manuscript will be fully rewritten to put our study in a general context.

We will first include a general paragraph on extreme flooding events in mountainous terrain mentioning previous severe events such as the flood in the mountainous catchments of central Europe in June 2013 (Grams et al., 2014), the Colorado Flood in September 2013 (Gochis et al., 2015) or previous flooding events in the mountains of Western Canada (Buttle et al., 2016). These events were characterised by large amount of rainfall strongly influenced by the local topography (e.g. Friedrich et al., 2016). In late spring, these heavy rainfall can occur with high-freezing level leading to a rain-on-snow (ROS) event in areas that are still covered by snow (Mc Cabe et al., 2007; Corripio and Lopez-Moreno, 2017). The June 2013 Flood in Alberta corresponds to this type of event (Pomeroy et al., 2016). We will then briefly detail the main hydro-meteorological features of this extreme event.

We will then write paragraphs on the modelling strategies that are used to predict these extreme events (e.g. Hapuarachchi et al., 2011; Pagano et al. , 2014). In particular, we will discuss the main source of uncertainties for operational flood forecasting in complex terrain (Mascaro et al., 2010, Zappa et al., 2011). We will highlight the importance of the spatial and temporal accuracy of the rainfall forcing (e.g. Jasper et al., 2002; Vincendon et al., 2011, Lobligeois et al., 2014). The influence of initial soil moisture and snow conditions will be discussed as well (e.g. Anquetin et al., 2010 , Silvestro and Rebora, 2010; Edouard et al. 2018). In particular, we will mention the benefit for runoff prediction of using snow information from a dedicated external snow monitoring system (Jörg-Hess et al., 2015; Griessinger et al., 2016). Finally, the uncertainties associated with the soil dataset will be mentioned (Lovat et al., 2019).

A specific paragraph presenting the challenges of ROS modelling will then be written. We will mention past studies focusing on specific hydrological prediction of rain-on-snow events (Rössler et al., 2014, Corripio and Lopez-Moreno, 2017) and the main conclusions from these studies. In particular, we will insist on the importance of an accurate estimation (i) the areal extent and snow water equivalent at the beginning of the ROS (McCabe et al., 2007) (ii) the contribution of the turbulent fluxes to total snow melt during ROS events (e.g. Marks et al., 1998; Garvelmann et al., 2014; Würzer et al., 2016) and (iii) the evolution of the rain/snow partitioning during the event (Jasper et al., 2002) and the potential benefit of the phase partitioning from cloud microphysical schemes implemented in atmospheric models (Harpold et al., 2017). We will also mention the influence of the initial snowpack properties at the beginning of the ROS (e.g. Würzer et al., 2016).

We will finally describe the scientific objectives of this paper and give an overview of the modelling strategy.

The list of the references mentioned here is given at the end of this document.

Specific Comments:
P1L28-29: How could the results of this study guide the development of the hydrological forecasting system worldwide?
Our answers to the two above general comments show how our study can contribute to the improvement of the general knowledge on flood modelling in complex terrain. Therefore, we believe that our results are interesting for the international community working in this subject. The Abstract will be re-written to better highlight the general contribution of our study.

P4L10: Could the authors comment on the consistency of these four different networks?
These four different meteorological have been deployed for different purposes. For example, the SYNOP and ABE stations are well distributed across Alberta to provide a permanent monitoring of weather conditions across the province. On the other hand, CRHO stations are distributed around targeted mountainous catchments and provide very valuable information in poorly observed areas by the other networks. CaPA has been designed to deal with different precipitation networks and insure the consistency of the precipitation data when they are included in the analysis. A spatial consistency test is applied in the Quality-control (QC) procedures of CaPA to identify and remove observations with large errors from the final analysis. The QC procedures are detailed in Lespinas et al. (2015). We will add in the revised manuscript a comment on the consistency of the different networks and mention the QC procedures used in CaPA.

P5L3-4: What are the drainage areas of these river basins?
The answer to this question is given in Table 1 shown below.

P5L6-7: Could the authors provide the basic information of these 10 stations (e.g. station name, drainage area, name of tributary)?
As mentioned above in our answer to the first of the general comments and as proposed by Reviewer 3 in one of his following comment, a new set of 12 stations will be used for model evaluation in the revised manuscript. This new set of stations will consist of the main unregulated stations located in the headwaters of the Oldman, Bow and Red Deer Rivers basins. In the revised manuscript, we will include a table that provides the main information for the hydrometric stations used for model evaluation. A preliminary version of this table is given below and a map showing the location of the stations is shown in our answer to one of the following specific comments. (Figure 2).

Table 1. Characteristics of the hydrometric stations proposed for model evaluation in the revised manuscript

Station Code	Station Name	Drainage Area (km^2)	Included in the initial paper
05CA004	Red Deer River Above Panther River	941	No
05CA009	Red Deer River Below Burnt Timber Creek	2246	No
05BB001	Bow River at Banff	2210	No
05BG010	Ghost River Above Waiparous Creek	484	No
05BH015	Jumpingpound Creek at Township Road	474	Yes
05BJ010	Elbow River at Sarcee Bridge	1189	Yes
05BL012	Sheep River at Okotoks	1494	Yes
05BL019	Highwood River at Diebel's Ranch	774	Yes
05AB041	Willow Creek at Oxly Ranch	833	No
05AA035	Oldman River at Range Road	1835	No
05AA008	Crowsnest River near Franck	403	No
05AA022	Castle River near Beavers Mines	820	No

P10L10-12: It would be better to provide the performance measures (Bias, RMSE, R2) of each basin in a table.
A table containing the performances measures for each CaPA experiment and each main basin will be added to the revised manuscript.

P10L13-14: Could the authors explain how the negative bias was removed by increasing the spatial resolution to 2.5km and 1km? Figures 7c) and 7d) do not show an obvious removal of the negative bias, instead, the points are still scattered above and below the 1:1 line.
Improvements in the precipitation analysis from 10 km to 2.5 km and 1 km resulted from improvements in the precipitation background provided by the Canadian NWP system GEM. GEM at 2.5 km and 1 km resolves explicitly part of the convection with the cloud microphysical scheme P3 whereas all the convection is parameterised in GEM at 10 km. Previous studies by Li et al. (2017) and Milrad et al. (2017) showed that atmospheric models at convection-permitting resolution performed best for this event. As detailed by Milrad et al. (2017), this is mainly due to (i) an improved representation of the orographic ascent that contributed to the magnitude of the extreme rainfall (ii) an anchoring and increasing duration of the precipitation on the Eastern side of the Rockies. Compared to the analysis at 10 km, the bias has been improved at 2.5 and 1 km since the points are better centred around the 1:1 line. However, as mentioned by Reviewer 3, these points are still scattered around this line with leads to similar RMSE. Better explanations will be given in the revised version of the manuscript.

P10L15-16: Could the authors explain why there were overestimations of cumulative precipitation using CaPA 1.0km?
GEM at 1 km explicitly simulated most of the convection with its cloud microphysical scheme. This led to the explicit representation of organised high-precipitation cells during the convective stage of this extreme rainfall event. However, the exact location of these precipitation cells was not necessarily well captured by the atmospheric model. Therefore, GEM at 1 km simulated unrealistically high-

accumulation at some locations that were not systematically corrected by CaPA during the leave-one-out evaluation. More details will be added in the revised manuscript.

P11L1-2: While the analysis on the effects of spatial resolution, gauge network density, and initial snow condition were conducted across the Oldman, Bow, and Red Deer River basins, the hydrological simulations were evaluated on Jumpingpound Creek, Elbow River and Highwood River, which are all located within the Bow River basin. I think such selection of hydrological simulations could not fully reveal the impacts of those factors controlling the flood dynamics. A better experimental design could be selecting one or two headwater sub-basins from each river basin (Oldman, Bow, and Red Deer). The results could potentially provide more information than the current setting (10 stations all within the Bow River basin) especially when different responses were witnessed after the inclusion of additional information (precipitation and/or SWE) across the three basins (e.g. consistently underestimation of cumulative precipitation plus overestimation of SWE in the Bow River, a mixture of over-and under-estimation of cumulative precipitation in the Red Deer, and underestimation of cumulative precipitation plus fairly accurate SWE estimates in the Oldman River). I wonder why the authors only focused on hydrological simulations within the Bow River basin.
Only hydrometric stations within the Bow Rover basin were selected in the initial manuscript since we focused our evaluation of hydrological simulations over one of the area that was the most severely impacted during the flooding event and that was monitored by a relatively dense network of hydrometric stations. We agree with Reviewer 3 that this selection of stations limited our ability to analyse the impact of the different factors governing the flood dynamics.
Following this comment, a better experimental design will be used in the revised manuscript. 12 unregulated stations located in the headwaters of the Red Deer (2 stations), Bow (6 stations) and Oldman (4 stations) River basins will be selected for the evaluation of hydrological simulations. Among these 12 stations, 4 stations were used in the initial manuscript. The location of these stations is given on the map below and their main characteristics are reported in the table on the previous page. In total, the river basins of these 12 stations cover 12700 km^2 and were characterised by different total

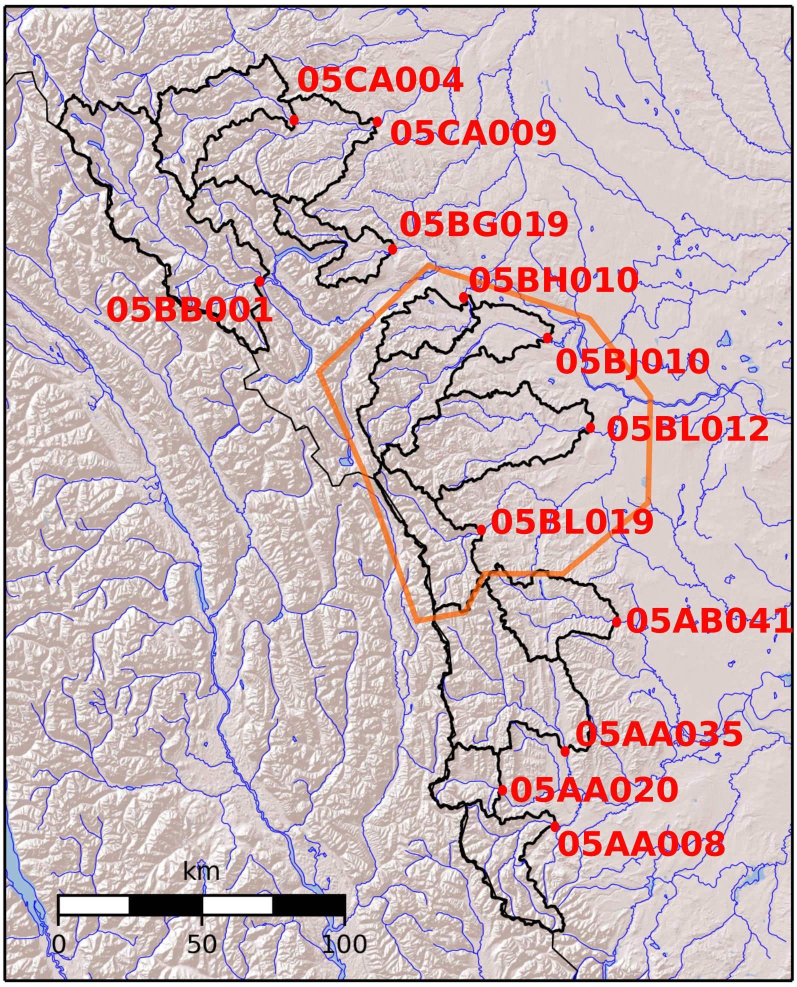

Figure 2. Location of the 12 hydrometric stations proposed for the evaluation of hydrological simulations in the revised manuscript. The black lines represent the limits of the catchments associated with each station. The orange polygon delineates the area that was studied in the initial

precipitation amount, initial snowpack conditions and soil characteristics. We strongly believe that this new set of stations, not restricted to the Bow river basin, will improve the credibility of our study and bring interesting discussions on the main factors controlling the flow dynamics for contrasted regions.

P15L30-P16L15: This study did not examine the model structure and the process representation in the model at all. Providing a list of potential reasons that might affect the model performance here becomes irrelevant unless concrete proof and result analysis are given to show the underlying causal relationship. This sub-section should be better re-written.
We will carefully review this sub-section and rewrite it to be more consistent with the results shown in our study. We will keep in the revised manuscript a part of the discussion where the limitations of the land surface scheme SVS for mountain hydrology are mentioned.

P17L19-20: What about the ground station data from the ABE, CHRO, and COOP networks? Are they publicly available to the international readers?
All the data from the ABE, CRHO and COOP networks are available to the international readers through requests on dedicated web-portals. Data from ABE stations can be downloaded at: https://agriculture.alberta.ca/acis/alberta-weather-data-viewer.jsp. CHRO data are available via the web portal: http://giws.usask.ca/meta/. Finally COOP data are available at https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop . The section *Data availability* of the revised manuscript will include these links.

Remarks:
P2L4-5, 10, and 12: could the authors check this reference please? Is this reference the correct one that the authors intended to use? I guess it should be Pomeroy et al. 2016a. Please correct me if I am wrong.
Indeed we were using the wrong reference. The correct one is Pomeroy et al (2016b) and we will make the correction in the revised manuscript.
Pomeroy, J. W., R. E. Stewart, and P. H. Whitfield. The 2013 flood event in the South Saskatchewan and Elk River basins: Causes, assessment and damages. Can. Water Resour.. J. 41 (1-2), ,https://doi.org/10.1080/07011784.2015.1089190, 2016b

We will incorporate the below corrections in the revised manuscript.

P8L18: should be "similar to" not "similarly to"

P8L24 and 27: please spell out the full name first before using the abbreviation

P8L33: missing full stop after "(18 June 2013)"

P12L5: should it be "Fig. 10c, f and Fig. 11c, f" instead of " Fig. 10d, f and Fig. 11d,f"?

P12L23: better use "hypothesis" instead of "assumption"

P17L15: delete "are"

Figures 3 and 4: better use "boundaries" instead of "limits"
The legend of the two figures will be modified according to this comment.

Figures 10-12: it is a bit misleading to use filled area to represent the results because essentially there are only two simulations using initial conditions from OPL and SND. They might not necessarily represent the upper and lower limits of the model performance, especially when more different initial conditions are used.
We agree with Reviewer 3 and the filled area will be systematically removed from the figures showing hydrographs in the revised manuscript.

List of references that will included in the introduction (not exhaustive):

Anquetin, S., Braud, I., Vannier, O., Viallet, P., Boudevillain, B., Creutin, J. D., & Manus, C. (2010). Sensitivity of the hydrological response to the variability of rainfall fields and soils for the Gard 2002 flash-flood event. *Journal of hydrology*, *394*(1-2), 134-147.

Buttle, J. M., Allen, D. M., Caissie, D., Davison, B., Hayashi, M., Peters, D. L., ... & Whitfield, P. H. (2016). Flood processes in Canada: Regional and special aspects. *Canadian Water Resources Journal/Revue canadienne des ressources hydriques*, *41*(1-2), 7-30.

Corripio, J., & López-Moreno, J. (2017). Analysis and Predictability of the Hydrological Response of Mountain Catchments to Heavy Rain on Snow Events: A Case Study in the Spanish Pyrenees. *Hydrology*, *4*(2), 20.

Edouard, S., Vincendon, B., & Ducrocq, V. (2018). Ensemble-based flash-flood modelling: Taking into account hydrodynamic parameters and initial soil moisture uncertainties. *Journal of Hydrology*, *560*, 480-494.

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Garvelmann, J., Pohl, S., & Weiler, M. (2014). Variability of observed energy fluxes during rain-on-snow and clear sky snowmelt in a midlatitude mountain environment. *Journal of Hydrometeorology*, *15*(3), 1220-1237.

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsch, M., Sun, J., ... & Matrosov, S. (2015). The great Colorado flood of September 2013. *Bulletin of the American Meteorological Society*, *96*(9), 1461-1487

Grams, C. M., Binder, H., Pfahl, S., Piaget, N., & Wernli, H. (2014). Atmospheric processes triggering the central European floods in June 2013. *Natural Hazards and Earth System Sciences*, *14*(7), 1691-1702.

Griessinger, N., Seibert, J., Magnusson, J., & Jonas, T. (2016). Assessing the benefit of snow data assimilation for runoff modeling in Alpine catchments. *Hydrology and Earth System Sciences*, *20*(9), 3895-3905.

Hapuarachchi, H. A. P., Wang, Q. J., & Pagano, T. C. (2011). A review of advances in flash flood forecasting. *Hydrological processes*, *25*(18), 2771-2784.

Harpold, A. A., Kaplan, M. L., Klos, P. Z., Link, T., McNamara, J. P., Rajagopal, S., Schumer, R., and Steele, C. M.: Rain or snow: hydrologic processes, observations, prediction, and research needs, Hydrol. Earth Syst. Sci., 21, 1–22, https://doi.org/10.5194/hess-21-1-2017, 2017.

Jasper, K., Gurtz, J., & Lang, H. (2002). Advanced flood forecasting in Alpine watersheds by coupling meteorological observations and forecasts with a distributed hydrological model. *Journal of hydrology*, *267*(1-2), 40-52.

Jörg-Hess, S., Griessinger, N., & Zappa, M. (2015). Probabilistic forecasts of snow water equivalent and runoff in mountainous areas. *Journal of Hydrometeorology*, *16*(5), 2169-2186.

Lobligeois, F., Andréassian, V., Perrin, C., Tabary, P., and Loumagne, C.: When does higher spatial resolution rainfall information improve streamflow simulation? An evaluation using 3620 flood events, Hydrol. Earth Syst. Sci., 18, 575–594, https://doi.org/10.5194/hess-18-575-2014, 2014.

Lovat, A., & Vincendon, B. (2019). Assessing the impact of resolution and soil datasets on flash-flood modelling. *Hydrology and Earth System Sciences*, *23*(3), 1801-1818.

Marks, D., Kimball, J., Tingey, D., & Link, T. (1998). The sensitivity of snowmelt processes to climate conditions and forest cover during rain−on−snow: A case study of the 1996 Pacific Northwest flood. *Hydrological Processes*, *12*(10−11), 1569-1587.

Mascaro, G., Vivoni, E. R., & Deidda, R. (2010). Implications of ensemble quantitative precipitation forecast errors on distributed streamflow forecasting. *Journal of Hydrometeorology*, *11*(1), 69-86.

McCabe, G. J., Clark, M. P., & Hay, L. E. (2007). Rain-on-snow events in the western United States. *Bulletin of the American Meteorological Society*, *88*(3), 319-328.

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Silvestro, F., & Rebora, N. (2014). Impact of precipitation forecast uncertainties and initial soil moisture conditions on a probabilistic flood forecasting chain. *Journal of hydrology*, *519*, 1052-1067.

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Würzer, S., Jonas, T., Wever, N., & Lehning, M. (2016). Influence of initial snowpack properties on runoff formation during rain-on-snow events. *Journal of hydrometeorology*, *17*(6), 1801-1815.

Zappa, M., Jaun, S., Germann, U., Walser, A., & Fundel, F. (2011). Superposition of three sources of uncertainties in operational flood forecasting chains. *Atmospheric Research*, *100*(2-3), 246-262.