Improving Medium-Range Forecasts of Rain-on-Snow Events in Prealpine Areas

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Abstract Rain-on-snow (RoS) events have caused severe floods in mountainous catchments in the recent past. Challenges in forecasting such events are uncertainties in meteorological input variables, the accurate estimation of snow cover and deficits in process understanding during runoff formation. Here, we evaluate the potential of the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (ECMWF IFS) to forecast RoS disposition (i.e., minimum rainfall amounts, initial snow cover, and meltwater contribution) several days ahead. We thereby evaluate forecasts of rain and snowfall with disdrometer observations and show that ensemble-based forecasts have larger potential than the high-resolution forecast of ECMWF IFS. Then, we use ECMWF IFS weather forecasts as input to a conceptual hydrological model, which is calibrated using estimates of snow-covered area (SCA), snow water equivalent (SWE), and discharge observations. We show that the forecast skill of this model chain is reasonably high with respect to SCA and SWE, even several days ahead. However, a number of RoS events are missed in the forecast, mainly due to an underestimation of rainfall amounts. These misses can be reduced by lowering the rainfall amount threshold for the forecast as compared to the analysis, being accompanied by only a moderate increase in false alarm rates. In contrast, the forecast of RoS disposition is found to be less sensitive to thresholds of initial snow cover and meltwater contribution. We conclude that valuable disposition warnings for RoS events can be issued several days ahead, and we illustrate this idea with a case study.

1. Introduction

Rain-on-snow (RoS) floods, during which rain is falling on an existing snow cover, are a well-known flood type in temperate climate mountain rivers and can cause enormous runoff depths as a result of only moderate rainfall (Merz & Blöschl, 2003). This flood type is linked to many of the largest floods in the United States and Canada (Jeong & Sushama, 2018; Kattelmann, 1997; Leathers et al., 1998; Marks et al., 1998, 2001). Also in central Europe, studies show that 20% of the peak flows are associated with RoS events in Austria (Merz & Blöschl, 2003), and up to 80% in some parts of Bavaria (Sui & Koehler, 2001). RoS events with flooding potential have been found to particularly affect upland basins at elevations of around 200–1,500 m above sea level (a.s.l.; Freudiger et al., 2014; Sui & Koehler, 2001) and can cause considerable economic damage in these areas. For example, a RoS flood occurring on 10 October 2011 in the Swiss Prealps was associated with an economic damage in the order of 94 million US$ or an equivalent of 71% of all precipitation induced damage in that year in Switzerland (Andres et al., 2012). Although such RoS floods are quite rare in Switzerland and found to be less relevant for economic damages than long-lasting rainfall over longer time periods, snowmelt nevertheless increases the disposition to floods in large areas, such as in the case of the spring 1999 flood in Switzerland (Hilker et al., 2009). Also, during the January 1995 flood in Germany, rapid snowmelt from the Black Forest (reaching up to around 1,500 m a.s.l.) partly augmented peak discharge in the lower parts of the Rhine River, causing damage in major cities like Koblenz and Cologne (Fink et al., 1996; Ulbrich & Fink, 1995).

With ongoing climate warming, the occurrence of RoS events is expected to become more important in mountainous catchments in the near future, particularly at elevations above 1,500 m a.s.l. (Musselman et al.,...
In general, there exist strong regional differences in future projections of RoS occurrence, as such changes depend on both the air temperature and associated precipitation phase (rain or snowfall) as well as the areal extent and thickness of the snowpack: In midlatitude and lowland regions, the frequency of RoS events is expected to decrease due to snowpack declines. By contrast, RoS frequency is expected to increase in high latitude and mountainous regions due to a shift from snowfall to rain but persistent seasonal snow cover (Freudiger et al., 2014; Jeong & Sushama, 2018; McCabe et al., 2007; Musselman et al., 2018; Surfleet & Tullos, 2013; Ye et al., 2008). Furthermore, projected changes in RoS frequencies are depending on the investigated climate scenario and time horizon (Beniston & Stoffel, 2016; Morán-Tejeda et al., 2016) and might differ for different seasons (Jeong & Sushama, 2018). For Switzerland, Kömlin et al. (2014) predict a diversification of flood types in the wintertime as well as an increase of RoS floods in the future.

Medium-range forecasts of flood events are considered important to increase preparedness of local authorities and the population several days in advance of a potentially critical situation (Alfieri et al., 2012), and have been shown to substantially reduce economic losses in individual cases (Fink et al., 1996; Ulbrich & Fink, 1995). Despite the large damage potential of RoS floods, however, the forecast of such events remains challenging, because their occurrence depends not only on the rain intensity and amount but also on the prevailing freezing level and spatial distribution of snow cover (Würzer et al., 2016). The major uncertainties associated with predicting RoS events include the meteorological forecast of precipitation and the freezing level, estimates of the areal extent and water equivalent of the antecedent snowpack as well as the representation of RoS processes in the hydrological model (McCabe et al., 2007; Würzer et al., 2016). As shown by Rössler et al. (2014), these uncertainties played a major role for failure in predicting peak discharge during the above mentioned RoS event of October 2011 in Switzerland.

In contrast to studies aiming at forecasting discharge or peak flows during RoS events at shorter lead times, that is, several hours to few days ahead (Corripio & López-Moreno, 2017; Rössler et al., 2014), this study aims to improve the forecast of the occurrence of RoS events (or RoS disposition) several days ahead and thus to increase preparedness to such events in the medium range. Therefore, we use the European Centre for Medium-Range Weather Forecasts Integrated Forecasting System (ECMWF IFS) providing global weather forecasts at these lead times. First, we evaluate the forecasts of rain and snowfall of ECMWF IFS with local disdrometer observations. In particular, we compare the high-resolution (HRES) forecast with a newly developed ensemble-based product at ECMWF (Gascón et al., 2018), as improvements of precipitation type forecasts are expected from ensemble (ENS) forecasts in recent studies (Gascón et al., 2018; Fehlmann et al., 2018; Reeves et al., 2016). Second, weather forecasts of ECMWF IFS are used as input to a conceptual hydrological model to forecast the occurrence of RoS events up to 7 days ahead. This model chain is calibrated using satellite-derived estimates of snow-covered area (SCA), local estimates of snow water equivalent (SWE), and discharge observations in a calibration period of 10 years (2005–2015). During the validation period (2015–2018), we particularly focus on the forecast of RoS events. More specifically, the following research questions are addressed:

1. What is the potential of using ENS forecasts of rain and snowfall compared to the HRES forecast of ECMWF?
2. How accurate is the analysis of relevant hydrological variables (i.e., SCA, SWE, and discharge), and how does forecast skill with respect to these variables develop with increasing lead time?
3. Is it possible to forecast the disposition of RoS events (i.e., minimum rainfall amounts, initial snow cover, and meltwater contribution to discharge) and thus to issue valuable disposition warnings for such events several days ahead?

The paper is organized as follows: In section 2, the study area is shown, while available data used as input to the conceptual hydrological model as well as for its calibration and validation are described in section 3. In section 4, the hydrological model structure as well as the methodology for model calibration and validation are presented. Results are presented in section 5 and discussed in section 6. Finally, conclusions with respect to operational medium-range forecasting of RoS events are drawn in section 7.

2. Study Area

RoS events are analyzed in three catchments (i.e., Kander, Simme and Emme) in the Bernese Prealps, Switzerland (Figure 1). In total, these catchments cover an area of 1,991 km² (Kander: 491 km², Simme: 563 km², Emme: 1,001 km²).
Figure 1. Study area, shown on the national map 1:1 million from the Swiss Federal Office of Topography swisstopo. The conceptual hydrological model applied in this study is driven by meteorological fields of the ERA5 reanalysis data set (ERA5 grid) and the high-resolution forecasts (HRES grid) of ECMWF IFS as well as estimates of mean potential evapotranspiration derived from 12 meteorological stations in the study area. Calibration and validation of this model chain is based on snow and discharge observations, while disdrometer data are used for the verification of meteorological forecasts. ECMWF IFS = European Centre for Medium-Range Weather Forecasts Integrated Forecasting System.

km², Emme: 937 km²) and reach from 454–3,680 m a.s.l. (Kander: 650–3,680 m a.s.l., Simme: 665–3,240 m a.s.l., Emme: 454–2,215 m a.s.l.). The catchment hypsographies are shown in Figure 2.

Prealpine areas in this elevation range are of particular interest for the investigation of RoS events, as they can be covered with snow during an extensive time of the year, and shifts from snowfall to rain due to climate change might lead to an increased RoS frequency in the near future. Also, snow cover in these areas is usually temperate and snowpack conditions are more homogeneous than in higher alpine areas, where more complex snow models might be necessary to capture the relevant snowpack properties during RoS events (Würzer et al., 2016). Finally, catchment areas at this elevation can be considerably large and contribute to peak discharge of larger catchments further downstream.

The investigation of the Bernese Prealps allows to study more extensively the above mentioned RoS flood of 10 October 2011. During this event, discharge of the Kander River at Hondrich (see Figure 1) rose up to 265 m³/s within a few hours, which is the second highest discharge ever measured at this station in the period between 1981 and 2018. Also, the Simme River was affected by RoS conditions during this event, although the peak discharge of 145 m³/s at Latterbach (see Figure 1) was statistically less extreme than in the Kander River. Noteworthy, both of these rivers are draining into the lake of Thun, which rose considerably during this event and had to be drained through a flood relieve tunnel, leading to a rising of the Aare River in the city of Thun and further downstream in the city of Bern.

3. Data
3.1. ECMWF Model Outputs
In this study, different outputs of ECMWF global weather models are used for different purposes (Table 1).
Figure 2. Hypsographies of the three investigated catchments (Kander, Simme and Emme). In total, these catchments cover an area of 1,991 km$^2$ and reach from 454–3,680 m a.s.l.

First, we assess the meteorological input data, that is, precipitation phase forecasts of ECMWF IFS, which have major implications for the forecast of RoS events in prealpine areas. Thereby, we compare forecasts of rain and snowfall by the ECMWF HRES as well as the ECMWF ENS model to local disdrometer observations. While the HRES model provides a single deterministic forecast, the ENS model consists of one control and 50 perturbed forecasts providing an estimate of the currently understood range of uncertainty in the observations and the model. When comparing precipitation phase forecasts to local observations, the difference in elevation between the model and the true orography at observation sites can be an important source of uncertainty in the verification process (Gascón et al., 2018). For this reason, we consider a model grid point located at a similar elevation and at a distance of 25 km to the disdrometer for both the HRES and the ENS model (Fehlmann et al., 2018). For this grid point, the variables of instantaneous precipitation type and instantaneous precipitation rate are processed according to Gascón et al. (2018) and aggregated to the categories of rain and snow (including wet snow) with a temporal resolution of 3 hr.

Second, we use ECMWF global weather model outputs as input to a conceptual hydrological model to forecast RoS events. This model chain is calibrated and validated using both snow and discharge observations.

| Purpose               | Time period | System used | Temporal resolution | Spatial resolution |
|-----------------------|-------------|-------------|---------------------|--------------------|
| Input data assessment | 2017–2018   | HRES        | 3 hr                | 0.125°             |
|                       |             | ENS         | 3 hr                | 0.25°              |
| Model calibration     | 2005–2015   | ERA5        | 1 hr                | 0.25°              |
| Model validation      | 2015–2018   | ERA5        | 1 hr                | 0.25°              |
|                       |             | HRES        | 1–6 hr              | 0.125°             |
|                       |             | ERA5        | 1 hr                | 0.25°              |
|                       |             | HRES        | 1–6 hr              | 0.125°             |
|                       |             | ENS         | 3–6 hr              | 0.25°              |

Note. ERA5: ERA5 reanalysis data set; HRES: High-resolution forecast; ENS: Ensemble forecast.
Following a model-consistent approach, the ERA5 reanalysis data set (Copernicus Climate Change Service, 2017) is used as input during model calibration (2005–2015), while both ERA5 and the operational HRES forecast are used as input during model validation (2015–2018). The validation period of 2015–2018 was chosen in order to avoid large changes in the operational forecast models of ECMWF IFS during model validation. According to the specification of the hydrological model, the input variables of precipitation, temperature, temperature lapse rate, and wind speed from these models are averaged to daily resolution for each catchment. It should be noted that ERA5 and the operational HRES forecast differ in model resolution: While the native resolution is approximately 31 km for ERA5 and 9 km for the operational HRES forecast, we use model outputs interpolated to regular latitude-longitude grids of 0.25° and 0.125°, respectively. To assess the importance of this change in resolution between the analysis and the forecast, we validate the model using HRES forecasts in the resolution of both 0.125° as well as an artificially reduced resolution of 0.25°.

Third, we investigate the case study of the above mentioned RoS event occurring on 10 October 2011. This analysis is complementary to the systematic model validation (2015–2018) and gives more insight into model performance during a specific event. For this case study, we also test the use of ECMWF ENS forecasts as input to the hydrological model, which allows forecasting the occurrence of RoS events in probabilistic terms. Because this case study was of particular interest to validate the presented approach, the period of 4–16 October 2011 was removed from the calibration period.

Whereas ECMWF HRES and ECMWF ENS forecasts are updated twice per day at 00:00 and 12:00 UTC, we only consider the model runs at 00:00 UTC in this study, in accordance with the daily resolution of the hydrological model. Furthermore, we consider lead times of 1–7 days for all of the analyses.

3.2. Disdrometer Data
Since early 2017, a Thies disdrometer is installed in the study area at 1,060 m a.s.l. (see Figure 1), which provides information about the precipitation type at the ground surface with a high temporal resolution of 1 min (Fehlmann et al., 2018). The disdrometer measures the attenuation of a laser beam (785 nm) by precipitation particles with an optical sensor. From the amplitude and duration of this attenuation, the diameter and fall velocity of precipitation particles are derived and translated into precipitation type by considering the statistical relation between these quantities (e.g., Gunn & Kinzer, 1949). Bloemink and Lanzinger (2005) show that resulting estimates of precipitation phase (i.e., solid, mixed, and liquid precipitation) agree quite well with observations from a manned station, the overall agreement being 91%. While the detection of mixed-phase precipitation remains a weak point of the sensor (Bloemink & Lanzinger, 2005), only solid and liquid precipitation are considered in this study. For this purpose, precipitation-type estimates, which are provided by the disdrometer in the format of surface synoptic observations (SYNOP table 4677 for observations of present weather), were reclassified to the classes of rain and snowfall using the same reclassification scheme as described in Gascón et al. (2018).

3.3. Snow Data
For the calibration and validation of the conceptual hydrological model, we consider two types of snow data, that is, satellite-derived estimates of SCA and local estimates of SWE, as these quantities have been shown to cover different aspects of the snow cover simulation (Chen et al., 2017).

Estimates of SCA are obtained from Moderate-resolution Imaging Spectroradiometer (MODIS) satellite images (Hall & Riggs, 2016b, 2016a), which have been shown to be particularly useful for the calibration and validation of a conceptual hydrological model by Parajka and Blöschl (2008b). The main limitation when estimating SCA from satellite images is the presence of clouds, which impedes the classification of the underlying land surface and thus limits data availability (Parajka & Blöschl, 2006). To deal with this issue, a number of interpolation procedures have been developed and have been shown to substantially increase data availability without losing quality with respect to model calibration (Parajka & Blöschl, 2008a, 2008b). We thus apply the methods proposed in Parajka and Blöschl (2008a) and developed further in Parajka et al. (2010), including three main steps, that is, (I) the combination of MODIS Terra and MODIS Aqua images on a pixel basis, (II) the spatial interpolation of snow cover based on a regional estimation of the snowline (see perimeter in Figure 1), and (III) the temporal interpolation of snow cover. While the temporal interpolation applied by Parajka and Blöschl (2008a) is based on the use of prior observations, other studies propose the use of subsequent observations (e.g., Gao et al., 2011) or a combination of both (e.g., Gafurov & Bárdossy, 2009). Here, subsequent images are used for the temporal interpolation, as this is thought to more accurately
capture snow cover dynamics during RoS events. This procedure results in a series of images depicting daily snow cover with a horizontal resolution of 500 m. For calibration and validation of the hydrological model, SCA for each catchment was further extracted from these images.

Estimates of SWE can be obtained from local snow depth measurements if the bulk snow density is known. In Switzerland, statistical relationships between snow depth and bulk snow density have been established for different seasons and geographical locations (Jonas et al., 2009). However, such approaches might suffer from limitations when applied to daily time series, being unable to represent transient phenomena such as the settling of recently fallen fresh snow (Jonas et al., 2009). In this study, we therefore use an approach employing settling curves for each snowfall event, which was originally proposed by Martinec (1977) and has more recently been adapted for hydrological purposes (Jörg-Hess et al., 2014, 2015). For each catchment, a representative snow station was determined by correlation analysis between observed and simulated SWE using initial parameter values, that is, Frutigen Ottere (2,020 m a.s.l.) for the Kander, Färmel (1,970 m a.s.l.) for the Simme and Napf (1,404 m a.s.l.) for the Emme catchment (see Figure 1).

3.4. Other Data

Other data used as input to the conceptual hydrological model are the monthly potential evapotranspiration (PET) and the local topography. Monthly PET for the study area is estimated based on the Penman-Monteith equation proposed as a standard for reference evapotranspiration by the Food and Agriculture Organization of the United Nations (FAO; Allen et al., 1998). In Switzerland, the FAO reference evapotranspiration is calculated by the Swiss Federal Office of Meteorology and Climatology MeteoSwiss for all stations of the automatic monitoring network, which measure the relevant input variables (i.e., radiation, air temperature, air humidity and wind speed). To estimate monthly PET at the catchment scale, we use mean monthly values (2014–2018) of 12 stations in the study area (see Figure 1) and apply an adjustment to the elevation of each catchment as proposed by Lindström et al. (1997). The local topography is given by the digital elevation model swissALTI3D of the Swiss Federal Office of Topography swisstopo, which has a horizontal resolution of 2 m. From these data, the mean elevation and the relative area covered by each elevation band were extracted.

In addition to the snow data, discharge data are used for calibration and validation of the hydrological model. For the three catchments considered, observed stream flow discharge at daily resolution is provided by the Swiss Federal Office for the Environment FOEN.

4. Methods

4.1. Input Data Assessment

To compare precipitation phase forecasts of the ECMWF HRES and the ECMWF ENS model with respect to disdrometer observations, we use the concept of relative economic value (REV), which allows the assessment of both deterministic and probabilistic forecast systems in terms which are relevant to forecast users (Mylne, 2002). The REV can be interpreted as the value of a forecast system to a decision-maker faced with the uncertain prospect of some kind of severe weather event and assuming a simple cost-loss problem: The decision maker is able to protect against the effects of adverse weather by paying a certain cost, whereas the occurrence of adverse weather without protection results in a certain loss. The REV is then given as the expected monetary savings due to the forecast system, normalized to values of 1 for a perfect forecast and 0 for a climatological forecast. Given a climatological forecast, a decision maker will minimize the expenses by always protecting if the cost/loss ratio is smaller than the climatological frequency of adverse weather and never protecting otherwise. Whereas, given a perfect weather forecast, expenses are minimized by protecting when the cost/loss ratio is smaller than the forecasted probability of adverse weather, and not protecting otherwise (Wilks, 2001).

The REV of an imperfect forecast system is closely related to the receiver operating characteristic (ROC) curve, as both are a function of the hit rate and the false alarm rate of the system, in the case of probabilistic forecasts further depending on a user-specific probability threshold (Jolliffe & Stephenson, 2012). However, the ROC curve is insensitive to either conditional or unconditional biases and thus reflects potential rather than actual skill (Wilks, 2001). Consequently, while two forecast systems appear to have the same skill in a ROC diagram, their REV might differ from each other and between users with different cost/loss ratios (Jolliffe & Stephenson, 2012).
4.2. Hydrological Model

The hydrological model applied to forecast RoS events is a conceptual rainfall-runoff model, following the basic structure of the HBV-3 model (Bergström, 1976) and including a more detailed parameterization of melting processes (Anderson, 1973), as parameterizations of both latent and sensible heat fluxes are considered important for the simulation of snow cover dynamics during RoS events (Rössler et al., 2014). The use of a conceptual rainfall-runoff model has the advantage that dynamic factors affecting runoff production may be represented implicitly (Lamb, 1999). In particular, changing antecedent moisture conditions and snow cover are simulated continuously, both of which are important for runoff formation during RoS events. The model runs on a daily time step and consists of a semidistributed snow routine and a lumped runoff routine, which are schematically illustrated in Figure 3.

The snow routine simulates snow accumulation and melt in elevation bands of 100 m according to the snowmelt model of Anderson (1973), which combines a temperature-index method during radiation-melt situations (no rain periods) and a more detailed calculation of individual energy fluxes during advection-melt situations (rainy periods). At temperatures above \( T_{\text{lim}} \) (°C), these two melting situations are distinguished based on a minimum daily rainfall amount threshold \( R_{\text{lim}} \), which is set to 10 mm according to Anderson (1973) and coincides with the threshold for RoS conditions applied in this study (Musselman et al., 2018). At daily rainfall amounts below \( R_{\text{lim}} \), a radiation-melt situation is recognized according to equation (1):

\[
M_{\text{RAD}} = RMF(t) \cdot (T - T_{\text{lim}})
\]  

(1)

In this situation, snowmelt \( M_{\text{RAD}} \) (mm/day) is assumed to be dominated by the radiation components of the energy balance and is parameterized by a degree-day approach, that is, the difference of daily mean air temperature \( T \) (°C) to the chosen temperature threshold \( T_{\text{lim}} \), and a seasonally varied radiation-melt factor \( RMF(t) \) (mm/[day °C]), which is taking a minimum value of \( RMF_{\text{MIN}} \) on 21 December and a maximum value of \( RMF_{\text{MAX}} \) on 21 June with a sinusoidal interpolation in-between. When rainfall amounts exceed \( R_{\text{lim}} \), an advection-melt situation is recognized according to Anderson (1973):

\[
M_{\text{ADV}} = M^* + M_R + M_E + M_R
\]

(2)

\[
M^* = 1.2 \cdot T
\]

(3)
\[ M_H = (C1 + C2 \cdot u) \cdot T \quad (4) \]
\[ M_E = (C1 + C2 \cdot u) \cdot (e_s(T) - 6.11) / \gamma \quad (5) \]
\[ M_R = 0.0125 \cdot R \cdot T \quad (6) \]

In this situation, radiation melt \( M^* \) (mm/day) is calculated based on a simple parameterization of long-wave radiative exchange according to equation (3), that is, depending on daily mean air temperature \( T \) (°C), where the constant 1.2 (mm/[day °C]) is physically derived from the Stefan-Boltzmann equation for long-wave emittance. Melt due to sensible and latent heat \( M_H \) and \( M_E \) (mm/day) is further estimated by empirical wind functions according to equations (4) and (5), taking into account the influence of daily mean wind speed \( u \) (m/s) as a function of two wind coefficients \( C1 \) (mm/[day °C]) and \( C2 \) (mm/[day °C m/s]), as well as humidity via saturation water vapor pressure \( e_s(T) \) (mb), where \( \gamma \) denotes the psychrometric constant and is set to 0.65 (mb/°C). Finally, melt due to heat advected by rain \( M_R \) is calculated according to equation (6) as a function of both daily mean rainfall amount \( R \) (mm) and daily mean temperature \( T \) (°C).

At temperatures below \( T_{lim} \), snow is accumulating and possibly present liquid water within the snowpack is refreezing. Here, we use a similar method as found in Bergström (1976):

\[ RFR = CRFR \cdot RMF(t) \cdot (T - T_{lim}) \quad (7) \]

Thereby, the refreezing of water is calculated as negative melt RFR (mm/day) in analogy to equation (1), where CRFR is the refreezing coefficient.

The runoff routine represents changes in the soil moisture state of the catchment as well as runoff generation. Soil moisture storage is characterized by three model parameters: Maximum storage capacity (FC), soil moisture state above which evaporation is at its potential rate (LP), and a parameter relating runoff generation to the soil moisture state (b). Runoff generation is represented by an upper and a lower soil reservoir. Excess rainfall and meltwater enters the upper zone reservoir and leaves this reservoir through three paths, that is, (I) outflow from the reservoir based on a fast storage coefficient (K1), (II) percolation to the lower zone with a constant percolation rate (PERC), and if a threshold of the storage state (UZL) is exceeded, (III) through an additional outlet based on a very fast storage coefficient (K0). Water leaves the lower zone based on a slow storage coefficient (K2). While Bergström (1976) proposes an additional routing for larger catchments including water reservoirs or lakes, we do not apply a routing function in this study.

4.3. Model Calibration and Validation

For the calibration of the conceptual hydrological model, we adopt a two-stage calibration strategy as proposed, for example, by Chen et al. (2017). This strategy uses multisource data to calibrate model parameters sequentially for (I) the snow and (II) the runoff routine. By considering different data sources at different stages of the modeling, individual hydrological processes (e.g., snow accumulation and melting) and state variables (e.g., SCA and SWE) are expected to be represented more accurately than under calibration against discharge data only. For example, it has been shown by several studies that the inclusion of SCA observations in model calibration improves the performance of SCA simulation without degrading the simulation of discharge (e.g., Franz & Karsten, 2013; Riboust et al., 2019; Şorman et al., 2009). Furthermore, by including spatial information from remote sensing products, the spatial representation of such processes and variables is expected to improve with respect to standard calibration against point measurements, which is regarded as crucial for the simulation of RoS events (Würzer et al., 2016). Finally, by progressive calibration and evaluation at each stage of the simulation, error propagation is constrained and the problem of equifinality is resolved to some degree (Chen et al., 2017).

To measure the agreement between simulated and observed values during both stages of the simulation, we use the KGE’ (Gupta et al., 2009; Kling et al., 2012), which takes into account the Pearson correlation coefficient \( r \), the percentage bias \( \beta \), and the variability ratio \( \gamma \) between these values (equations (8)–(11)):

\[ KGE' = 1 - \sqrt{(r - 1)^2 + (\beta - 1)^2 + (\gamma - 1)^2} \quad (8) \]
\[ r = \frac{Cov_{so}}{\sigma_s \sigma_o} \quad (9) \]
Table 2
Summary of Optimized Model Parameters for the Three Catchments Considered

| Parameter | Unit | Kander | Simme | Emme |
|-----------|------|--------|-------|------|
| $T_{lim}$ | °C   | 1.53   | 1.45  | 1.64 |
| $R_{lim}$ | mm   | 10     | 10    | 10   |
| LWHC      | –    | 0.1    | 0.1   | 0.1  |
| CRFR      | –    | 0.05   | 0.05  | 0.05 |
| RMFMIN    | mm/(day °C) | 1.77 | 0.51 | 0.52 |
| RMFMAX    | mm/(day °C) | 3.13 | 3.68 | 3.75 |
| C1        | mm/(day °C) | 0.59 | 0.09 | 0.26 |
| C2        | mm/(day °C m/s) | 0.80 | 0.59 | 0.54 |
| FC        | mm   | 900    | 900   | 516  |
| LC        | –    | 0.72   | 0.45  | 0.4  |
| b         | –    | 0.54   | 0.68  | 1    |
| K0        | 1/day | 0.20   | 0.20  | 0.56 |
| K1        | 1/day | 0.20   | 0.17  | 0.41 |
| K2        | 1/day | 0.07   | 0.01  | 0.15 |
| UZL       | mm   | 70     | 60    | 22   |
| PERC      | mm/day | 5     | 1.83  | 1.29 |

\[
\beta = \frac{\mu_s}{\mu_o}
\]  

(10)  
\[
\gamma = \frac{\sigma_s/\mu_s}{\sigma_o/\mu_o}
\]  

(11)

where Cov_{so} is the covariance between the simulated and the observed values, $\mu$ is the mean, and $\sigma$ is the standard deviation (the indices s and o representing simulated and observed values, respectively). $KGE'$, $r$, $\beta$, and $\gamma$ have their optimum at unity and $KGE'$ is taking into account the Euclidean distance of its three components to this optimum (Gupta et al., 2009). The use of $KGE'$ is interesting from a hydrological perspective, because the simulation of a flow variable in general aims to reproduce its temporal dynamics (measured by $r$) as well as to preserve its distribution (measured by $\beta$ and $\gamma$) (Kling et al., 2012).

The objective functions used to calibrate the snow routine ($Obj_{Snow}$) and the runoff routine ($Obj_{Runoff}$) are given in equations (12) and (13), respectively, and are both maximized during calibration. While the snow objective combines $KGE'$ on SCA and SWE data, the runoff routine is calibrated using $KGE'$ on gauged discharge data. In the validation period, $Obj_{Snow}$ and $Obj_{Runoff}$ are further used as criteria to evaluate model performance.

\[
Obj_{Snow} = \frac{KGE'_{SCA} + KGE'_{SWE}}{2}
\]  

(12)  
\[
Obj_{Runoff} = KGE'_Q
\]  

(13)

Given the data availability, the model was warmed up for 9 months from 1 January to 30 September 2005, calibrated for the period of 1 October 2005 to 30 September 2015, and validated for the period of 1 October 2015 to 30 September 2018. The period of 4–16 October 2011 was removed from the calibration period, since this period was of interest for the validation of a case study. Following a model-consistent approach, ERA5 is used as input in the calibration period, while both ERA5 and the operational HRES forecast are used as input in the validation period. From a total of 15 model parameters, two parameters are fixed, namely the refreezing coefficient CRFR is set to 0.05, making refreezing 20 times less efficient than melting, and the liquid water holding capacity LWHC is set to 0.1, meaning that the snowpack can retain 10% of its dry mass as liquid water. These two values are often referred to in literature (Beven, 2012). The remaining parameters were estimated by automatic model calibration, using the SCE-UA automatic calibration procedure (Duan et al., 1992; 1994) to maximize equations (12) and (13) in both stages of calibration, respectively. Resulting model parameters are listed in Table 2.
Figure 4. Relative economic value of rain and snowfall forecasts by two products of ECMWF, that is, an ensemble-based product (ENS, left) and the high-resolution model (HRES, right). For the ensemble-based product, the maximum economic value of all possible strategies (one for each threshold value of the probability) is shown. Each line corresponds to a different lead time ranging from 1–7 days.

4.4. Definition of RoS Events

The definition of RoS events varies among different applications. While different qualitative and quantitative definitions for RoS events exist at different scales (e.g., at the point, elevation range, or catchment scale), many of them take into account criteria of minimum rainfall amounts and initial snow cover (Beniston & Stoffel, 2016; Freudiger et al., 2014; Merz & Blöschl, 2003; Würzer et al., 2016). In this study, we define RoS events at the catchment scale after Musselman et al. (2018), that is, as characterized by a daily rainfall amount ($R$) greater than 10 mm, initial SWE greater than 10 mm, and a contribution of meltwater ($M$) to discharge of at least 20%.

5. Results

5.1. Input Data Assessment

The value of precipitation phase forecasts of ECMWF IFS is investigated for both the HRES and the ENS forecast system. While the former is used as input to the conceptual hydrological model during model calibration (2005–2015) and validation (2015–2018) in this study, both HRES and ENS forecasts are used as input for the validation during the case study of October 2011.
5.2. Hydrological Model Performance

The performance of the conceptual hydrological model is assessed by evaluating $Obj_{\text{Snow}}$ and $Obj_{\text{Runoff}}$ (i.e., the objective functions used for calibration) as criteria of model performance in both the calibration and validation period and by visual inspection of simulated and observed variables.

Figure 5 compares the values of both $Obj_{\text{Snow}}$ and $Obj_{\text{Runoff}}$ between the calibration and the validation period for each of the investigated catchments. Regarding the analysis (using ERA5 as input), differences between these two periods remain small for both $Obj_{\text{Snow}}$ and $Obj_{\text{Runoff}}$, indicating no overfitting of parameters. Also, the determined model parameters seem to be well applicable to the forecast mode of the hydrological model (using HRES as input), as the skill of the analysis is comparable to the forecast skill at a lead time of 1 day. In particular, the effect of increased model resolution of the HRES model compared to ERA5 is very small, which could be inferred from a comparison of forecast skill when using the HRES forecast as input with a resolution of 0.125° and 0.25°, respectively. Regarding the evolution of forecast skill with increasing lead time, $Obj_{\text{Snow}}$ is remarkably stable, whereas $Obj_{\text{Runoff}}$ is slightly decreasing with increasing lead time, especially after 4–5 days. Finally, to better interpret forecast skill with respect to the simulation of snow (SCA and SWE), we introduce a benchmark referring to the simulated snow cover in ERA5. For all catchments investigated, the estimation of SCA and SWE using ERA5 as input to the conceptual hydrological model is thereby preferable to the use of direct SCA and SWE outputs from ERA5. When looking more closely at the snow simulation in ERA5 (i.e., the different components of $KGE_{\text{SCA}}$ and $KGE_{\text{SWE}}$ in the validation period), it can be seen that SCA is generally overestimated while SWE is generally underestimated by this benchmark approach. The overestimation of SCA in all the catchments is indicated by corresponding percentage biases.
Figure 6. Validation of modeled snow water equivalent (SWE) at 2,020 m a.s.l. (top), snow-covered area (SCA, middle), and discharge ($Q$, bottom) in the Kander catchment from 1 October 2016 to 30 September 2017. For SWE and SCA, direct ERA5 model outputs are shown as a benchmark. For this specific catchment and hydrological year, $KGE_{\text{SWE}}$ of the hydrological simulation (benchmark) is 0.70 (0.49), $KGE_{\text{SCA}}$ is 0.79 (0.42), and $KGE_Q$ is 0.84.

Examples of simulated and observed SWE, SCA, and discharge for the Kander catchment and a specific hydrological year (2016–2017) are shown in Figure 6. Simulated SWE is compared to local SWE estimates at 2,020 m a.s.l. (see Figure 1). While the general evolution of the snowpack and, in particular, the melting of the snowpack at the end of the winter season are well simulated, the simulation slightly underestimates SWE accumulation at the beginning of the winter season in this specific year. Regarding SCA, the simulation is in good agreement with satellite-based observations, although the simulation seems to slightly overestimate individual peaks of SCA as compared to the observation. When investigating direct outputs of SWE and SCA in ERA5 (benchmark), it can be seen that especially SCA simulation suffers from limitations due

of 1.34, 1.6, and 2.74 in the Kander, the Simme, and the Emme catchments, respectively. At the same time, SWE is underestimated particularly in the higher elevated catchments of Kander ($\beta = 0.42$) and Simme ($\beta = 0.45$). This indicates that the snowpack in ERA5 is generally simulated as too shallow, but at the same time remains too long in the simulation for the catchments considered in this study. In terms of bias, the simulation using ERA5 as input to the conceptual hydrological model performs much better, that is, with mean percentage biases of 1.14 and 0.92 for analyzed SCA and SWE, respectively.
to the coarse model topography: The highest point of the model topography in the considered perimeter being located at 2,262 m a.s.l. does not allow to resolve SCA below around 70% in the Kander catchment. Furthermore, ERA5 considerably underestimates SWE, which is systematically the case for the Kander and Simme catchment for all hydrological years in the validation period (2015–2018). Discharge simulations are in quite good agreement with the observations, capturing variability at both seasonal and daily time scales. However, deviations between simulation and observation tend to increase with increasing discharge.

5.3. Forecasts of RoS Events
RoS events are defined in this study at the catchment scale and according to simulations using ERA5 as input (R ≥ 10 mm, SWE ≥ 10 mm, M ≥ 20%). The temporal distribution of analyzed RoS events is shown in Figure 7. Thereby, 194 RoS events are used in the calibration period (2005–2015) and 70 RoS events are analyzed in the validation period (2015–2018). Typically, a distinct seasonality of such events can be observed depending on the hypsography of the catchment: While catchments at lower elevations (e.g., Emme) are mostly affected by RoS events during winter, catchments at higher elevations (e.g., Kander) are mostly affected by RoS events in early autumn or late spring, respectively. In agreement with this seasonal distribution, the RoS event of 10 October 2011 (indicated with a red square in Figure 7) is analyzed in the higher catchments of Kander and Simme, while initial snow cover was less than 10 mm and the contribution of meltwater to discharge well below 20% in the Emme catchment on this day.

The simulated contribution of the different energy balance components to snowmelt according to equations (3)–(6) is shown in Figure 8 for all analyzed RoS events (2005–2018). According to the simulation, mean contribution of net radiation to snowmelt is 34% over this time period, while the sensible and latent heat fluxes are found to be almost equally important, accounting for 33% and 27% of total snowmelt. Adveected energy from rain is less important with a mean relative contribution of 6%. Furthermore, relative contribution of the energy balance components is found to be relatively stable in the simulation over all the
Figure 9. Hit and false alarm rates (left) and reasons for misses (right) with respect to the analyzed rain-on-snow (RoS) events in the validation period (2015–2018). RoS events are defined based on hydrological simulation using the ERA5 reanalysis as input ($R \geq 10$ mm, $SWE \geq 10$ mm, $M \geq 20\%$), while hydrological forecasts are based on hydrological simulation using the high-resolution forecast of ECMWF as input. Forecasts are verified using two different rainfall thresholds, that is, $R_{lim} = 10$ mm (top) and $R_{lim} = 3$ mm (bottom).

studied events and the three catchments investigated. However, turbulent heat fluxes were found to be slightly more important in the lowermost catchment of Emme (mean: 65%) as compared to the catchments of Kander and Simme (mean: 56%), which are located at higher elevations.

Figure 9 (top left) depicts the hit and false alarm rate (Jolliffe & Stephenson, 2012) using ERA5 as analysis for the RoS events and lead times from 1 to 7 days from the HRES model as forecast. Despite a low false alarm rate, a number of RoS events are missed in the forecast, that is, the hit rate is falling below 0.5 already at a lead time of 2 days. Reasons for misses are mainly due to a missed threshold exceedance for forecasted rainfall amounts ($R \geq 10$ mm), followed by missed threshold exceedance for meltwater contribution to discharge ($M \geq 20\%$) and sometimes due to a combination of more than one reason (top right). Snow cover in terms of mean SWE is not a sensitive condition in the sense that threshold exceedance ($SWE \geq 10$ mm) is never the only reason for missing an analyzed RoS event with a lead time of up to 7 days for all the investigated cases.

More insight into the variability of these three variables in the forecast is shown in Figure 10, which shows deviations of the forecast (1–7 days ahead) with respect to the analysis for all the analyzed RoS events. Variability of forecasted SWE is thereby smallest, followed by variability of snowmelt and rainfall amounts. While deviations of forecasted SWE and snowmelt with respect to the analysis vary around zero, rainfall amounts seem to be systematically underestimated for all the considered lead times, confirming the above stated reason for missing some of the analyzed RoS events.

One possibility of dealing with this issue from the perspective of a decision maker is to adjust the minimum rainfall amount threshold ($R_{lim}$) for the forecast as compared to the analysis. The corresponding ROC curves are shown in Figure 11 (top left), which depicts the sensitivity of the hit and false alarm rate to changes of
Figure 10. Comparison of forecasted hydrological variables to the hydrological analysis during all rain-on-snow events, which are analyzed in the validation period (2015–2018). While hydrological simulation is based on the ERA5 reanalysis as input, hydrological forecasts are based on the high-resolution model of ECMWF as input. Deviations of the forecast from the analysis are shown for rainfall amounts, snow water equivalent (SWE) and snowmelt and distinct lead times (1–7 days). ERA5 = ERA5 reanalysis data set; ECMWF = European Centre for Medium-Range Weather Forecasts.

\( R_{\text{lim}} \) in the forecast. It can be seen that misses can be reduced with only moderate increase in false alarm rates by lowering \( R_{\text{lim}} \) to 3 mm. This threshold was found to result in a good compromise between high hit rates and low false alarm rates over all the lead times considered: Although a lowering of \( R_{\text{lim}} \) below 3 mm further increases the hit rates for longer lead times (5–7 days), this effect is much smaller for shorter lead times (1–4 days) while overall false alarm rates are increasing substantially. The analysis of the ROC curves for changes of the thresholds for initial snow cover (SWE\(_{\text{lim}}\)) and melt water contribution (M\(_{\text{lim}}\)) revealed that hit and false alarm rates are much less sensitive to the choice of these two thresholds than to the choice of \( R_{\text{lim}} \) (see other panels in Figure 11). Resulting hit and false alarm rates using \( R_{\text{lim}} = 3 \) mm in the forecast as well as the reasons for misses are shown in Figure 9 (bottom).

5.4. Case Study 2011

On the basis of the case study of October 2011, the possible potential of forecasting RoS events several days ahead is demonstrated. The atmospheric drivers of this RoS event were a sustained snowfall on the days preceding 10 October followed by the passage of an atmospheric river bringing warm and moist air toward the Alps. As a result, intensive rainfall was accompanied by a temperature increase that shifted the 0 °C line from 1,500 to 3,200 m a.s.l. in 24 hr with a maximum increase of 9 °C in 9 hr (Rössler et al., 2014). In the following analysis, we adjust the rainfall amount threshold \( R_{\text{lim}} \) for the forecast of RoS events (and the corresponding threshold for the recognition of an advection-melt situation in the hydrological model) to 3 mm as proposed above. Furthermore, we test the use of ECMWF ENS forecasts as input to the hydrological model for this case study, which allows forecasting RoS events in probabilistic terms. The probability of an RoS event is thereby calculated as the percentage of all the 50 perturbed ensemble members forecasting such an event.

Figure 12 shows the analyzed and forecasted rainfall and meltwater amounts contributing to catchment discharge as well as corresponding RoS conditions for the three catchments investigated. The RoS event was analyzed in the catchments of Kander and Simme, while snowmelt played only a minor role in the Emme catchment as only the upper part of this catchment was covered with snow at the beginning of the event (Figure 13). Although forecasted rainfall amounts for 10 October 2011 vary between lead times and are generally underestimated, they persistently exceed the proposed threshold of 3 mm being associated with advection-melt conditions in the hydrological model and allowing for the detection of an RoS event. As snowmelt is forecasted to substantially contribute to discharge on 10 October 2011, the occurrence of an RoS event can be forecasted quite persistently in the Kander and Simme catchment already several days ahead.
Figure 11. Receiver operating characteristic curves showing hit and false alarm rates with respect to analyzed rain-on-snow (RoS) events in the validation period (2015–2018) and lead times of 1–7 days. RoS events are defined based on hydrological simulation using the ERA5 reanalysis as input ($R \geq 10$ mm, $SWE \geq 10$ mm, $M \geq 20\%$), while hydrological forecasts are based on hydrological simulation using the high-resolution forecast of ECMWF as input. The forecast of RoS events is assessed by varying the corresponding thresholds (i.e., $R_{lim}$, $SWE_{lim}$, and $M_{lim}$) in the forecast as compared to the analysis. Selected combinations of thresholds are highlighted in the figure. ERA5 = ERA5 reanalysis data set; ECMWF = European Centre for Medium-Range Weather Forecasts.

When using the HRES forecast as input, some false alarms occur with respect to the timing of the RoS event, that is, the occurrence of an RoS event is forecasted persistently for 9 October 2011 and in some cases for 11 October 2011. In the Emme catchment, however, no false alarms occur, mainly because large parts of the catchment remained snow-free at the beginning of the event, which is correctly forecasted by the model. When using the ENS forecast as input, the occurrence of RoS events can be indicated in probabilistic terms. Although considering a range of uncertainty in the observations and the model with this approach, the resulting RoS forecasts seems to be quite specific in the sense that the probability of an RoS event occurring in the Emme catchment is forecasted to be 0% for all the lead times (except 2% for a lead time of 7 days). In the Kander and the Simme catchments, this probability reaches 100% 2 days ahead of the event and is higher than 80% already 4 days ahead. Furthermore, forecasted RoS probabilities on 9 or 11 October are
Figure 12. Analyzed and forecasted rainfall amounts and meltwater in the three catchments investigated as well as corresponding rain-on-snow (RoS) disposition. The forecast of RoS disposition is based on the high-resolution (yes/no) and the ensemble forecast of ECMWF (numbers indicate probabilities in %). Analyzed RoS disposition is given by $R \geq 10$ mm, $SWE \geq 10$ mm, and $M \geq 20\%$, while the rainfall amount threshold is adjusted to 3 mm for the forecasts. ECMWF = European Centre for Medium-Range Weather Forecasts; SWE = snow water equivalent.

much lower than on 10 October, which allows to better assess the likely timing of the event as compared to the use of the HRES forecast.

To provide a spatial verification of the forecast, Figure 13 depicts the forecast of the snow cover dynamics issued on 6 October 00:00 UTC and compared to satellite images. Table 3 depicts the corresponding area percentages of initial snow cover, additional snow accumulation from 6–9 October as well as complete snowmelt between 9 and 11 October. Thereby, only small parts were snow covered on 6 October in all of the catchments (0% in the Emme and a maximum of 8% in the Kander catchment), which is well represented in the model. Also, areas affected by additional snow accumulation from 6–9 October (reaching up to 78% in the Kander catchment) are well simulated in the forecast. Regarding the melting period between 9 and 11 October, areas affected by complete snowmelt are slightly overestimated in the catchments of Kander and Simme (by 9% in both catchments), both of which were affected by RoS conditions on 10 October.
Figure 13. Observed and simulated changes in snow cover between 6–9 (top) and 9–11 October 2011 (bottom). Observed changes in snow cover (left) are derived from MODIS satellite images. Snow cover simulation (right) is based on the ERA5 reanalysis and the high-resolution forecast of ECMWF, issued on 6 October 00:00 UTC (i.e., with a lead time of 1–5 days), as well as the local topography as input to a conceptual hydrological model.

MODIS = Moderate-resolution Imaging Spectroradiometer; ERA5 = ERA5 reanalysis data set; ECMWF = European Centre for Medium-Range Weather Forecasts.
Table 3
Observed and Simulated Changes in Snow Cover From 6–11 October 2011

| Catchment | Initial snow cover (6 October) | Snow accumulation (6–9 October) | Snowmelt (9–11 October) |
|-----------|-------------------------------|-------------------------------|-------------------------|
|           | Obs  | Sim  | Obs  | Sim  | Obs  | Sim  |
| Kander    | 8%   | 7%   | 78%  | 78%  | 37%  | 46%  |
| Simme     | 2%   | 1%   | 76%  | 72%  | 54%  | 63%  |
| Emme      | 0%   | 0%   | 14%  | 8%   | 10%  | 8%   |

Note. Observed changes in snow cover (Obs) are derived from MODIS satellite images. Snow cover simulation (Sim) is based on the ERA5 reanalysis and the HRES operational forecast of ECMWF IFS, issued on 6 October 00:00 UTC (i.e., with a lead time of 1–5 days), as well as the local topography as input to a conceptual hydrological model.

Noteworthy, discharge in the Kander catchment is highly underestimated using both ERA5 and the operational HRES forecast as input. This can at least partly be attributed to a strong underestimation of precipitation amounts in both ERA5 and the operational HRES forecast as compared to observations at meteorological stations on 10 October 2011: While ERA5 simulates a precipitation amount of 26 mm, the operational HRES precipitation forecasts range from 11.5–24.4 mm for lead times of 1–7 days, which is consistent with the above stated general underestimation of precipitation amounts in the forecast as compared to the reanalysis. However, 53.4 and 55.7 mm of precipitation were measured on this day at the stations of Adelboden and Kiental in the Kander catchment, respectively. It is further interesting to note here that precipitation amounts were highly underestimated by the ENS forecast as well: For lead times of 1–7 days, the ensemble mean ranges from 5.9–17.9 mm, while the maximum precipitation amount of all the members ranges from 24.8–34.8 mm.

6. Discussion
Uncertainties in meteorological input data are one of the key sources of uncertainties in flood forecasting (Beven, 2012). As precipitation phase has major implications for the occurrence of RoS events, we assess the potential of using ensemble-based forecasts of rain and snowfall as compared to the ECMWF HRES forecast. By analyzing relative economic value (REV), we show that the ECMWF ENS is of larger value than the ECMWF HRES forecast with respect to the forecast of rain and snowfall for a given lead time of 1–7 days, and is giving value to a greater number of users with different cost/loss ratios than the ECMWF HRES forecast. The improvement of precipitation type forecasts by ensemble-based approaches is expected by several studies (Fehlmann et al., 2018; Forbes et al., 2014; Gascón et al., 2018), although a systematic comparison between these two forecast systems with respect to precipitation phase has not been carried out so far. Also, the result is consistent with studies comparing REV of probabilistic and deterministic forecasts for other meteorological variables such as temperature (Richardson, 2000) or wind speed (Mylne, 2002). Thereby, the main advantage of probabilistic information is that it allows users to choose a probability threshold for decision making according to their specific needs (i.e., their cost/loss ratio) and thus to maximize the forecast value. By analyzing forecast value rather than forecast skill, such practical advantages with regard to decision making can be expressed. An application of REV in hydrology can be found in Fundel and Zappa (2011), where the benefit of using reanalysis data to calibrate ensemble runoff forecasts is illustrated with this concept.

The analysis of the hydrological model performance supports the use of ERA5 as input during model calibration, as the skill of the analysis (using ERA5 as input) is comparable to the forecast skill at a lead time of one day (using the HRES forecast as input). Using a frozen model rather than actual meteorological measurements as input during calibration has the advantage not to introduce any systematic deviations between the analysis and the forecast, as, for example, due to the undercatch of snowfall in the measurements (Fassnacht, 2004; Savina et al., 2012), and such model-consistent approaches are also applied in other flood forecasting applications (e.g., Alfieri et al., 2011). Furthermore, as also highlighted by Fundel and Zappa (2011), using reanalysis data for the calibration of hydrological forecasts is an advantage in unobserved catchments.
By using ERA5 during model calibration and global weather models as input for the forecasting, the presented approach can be easily transferred to other geographical contexts and in particular to unobserved catchments.

When evaluated over the whole time series, we show that forecast skill with respect to snow cover (SCA and SWE) is reasonably high, even several days ahead, which is an important prerequisite to forecast RoS events, two of the applied criteria (SWE ≥ 10 mm, M ≥ 20%) being related to snow cover. The persistence of forecast skill with respect to SCA and SWE at these lead times can partly be related to the importance of the initial state. Regarding the analysis of the initial state of SCA and SWE, we show that the use of ERA5 as input to the hydrological model is preferable to the use of direct SWE outputs of ERA5. In particular, SWE is considerably underestimated by ERA5 for the two snow stations located at higher elevations in this study (at 1,970 and 2,020 m a.s.l., respectively). This finding is consistent with findings of a recent study comparing ERA5-driven simulations of snow depth with in situ observations and showing considerable negative biases in the simulation, particularly during the snow season and in mountainous areas (Albergel et al., 2018). We thus may speculate that this is related to the coarse representation of the mountain topography in ERA5. Finally, the simulation (and benchmark) of SCA seems to perform better in the catchments located at higher elevations, that is, the Kander and the Simme catchment, which can be related to the fact that more consecutive days with full snow cover are found at high altitude (Zappa, 2010).

Regarding the forecast of RoS events, a number of events are missed in the forecast due to an underestimation of daily rainfall amounts (i.e., a missed threshold exceedance for R ≥ 10 mm) for these events. One possibility to deal with this issue from the perspective of a decision maker is to lower the rainfall amount threshold Rlim, in the forecast as compared to the analysis, and to accordingly adjust the threshold Rlim, for the recognition of an advection-melt situation in the hydrological model. We show that with Rlim = 3 mm, hit rates can be increased with only a moderate increase in false alarm rates, the latter being constrained by the remaining RoS criteria (SWE ≥ 10 mm, M ≥ 20%). Rainfall amount thresholds applied for the identification of RoS events vary greatly between different studies and are possibly related to catchment size. For example, a rainfall amount threshold of 3 mm is applied to identify potentially flood-generating RoS events in larger river basins by Freudiger et al. (2014), while Beniston and Stoffel (2016) apply a threshold of 50 mm for a relatively small mountainous catchment (340 km²). Here, we have evidence that this threshold might additionally depend on the considered model resolution and propose to apply a different threshold for ERA5 as compared to the HRES forecast of ECMWF. Alternatively to the adjustment of rainfall amount thresholds, the particular underestimation of high precipitation amounts can be corrected by statistical postprocessing, as was, for example, developed for the ENS forecast of ECMWF by Verkade et al. (2013). The application of such procedures is regarded here as particularly important when modeling peak discharge at shorter lead times. In the presented case study of 10 October 2011, for example, the underestimation of rainfall amounts in the forecast as compared to observations at meteorological stations is found to be a major reason for the large underestimation of discharge during this event. This finding is consistent with results by Rössler et al. (2014) for the Lonza catchment, which is located adjacent to the Kander catchment and was also heavily affected by this event. However, and despite uncertainties in forecasted rainfall amounts, we conclude that the presented approach is able to forecast RoS disposition in the Kander and Simme catchment during this event with a high persistence already several days ahead. However, the analysis of additional events is needed to corroborate this preliminary finding.

The choice of an adequate parameterization of the energy balance is crucial when simulating RoS events. It has been shown exemplary that temperature-index approaches are not able to simulate the rapid snowmelt during such events, because they do not adequately represent turbulent (i.e., latent and sensible) heat fluxes (Rössler et al., 2014). Therefore, Rössler et al. (2014) suggest a more physically based approach, which has been applied in this study. To demonstrate the ability of this approach to represent the relevant energy balance components during RoS events, we compare the simulation results to studies applying physically based snow energy balance models at well-instrumented measurement sites. Thereby, turbulent heat fluxes have been shown to considerably enhance snowmelt during RoS events, accounting for around 60–90% of the snowmelt energy balance at the point scale (e.g., Garvelmann et al., 2014; Marks et al., 1998, 2001; Würzer et al., 2016). This dominant contribution of turbulent heat fluxes seems to be well represented by the chosen approach in this study, simulating these fluxes to account for 60% of total snowmelt during all of the 264 analyzed RoS events (2005–2018). In contrast, the effect of net radiation on snowmelt is known to be reduced during RoS events as compared to clear-sky situations, mainly because incoming shortwave radiation is
reduced due to cloud cover (Garvelmann et al., 2014; Mazurkiewicz et al., 2008). This is well represented by the presented approach by the distinction of advection and radiation melt situations, which results in a mean contribution of net radiation to snowmelt of only 34% during RoS events. Heat advected by rain has been shown to contribute little to snowmelt during RoS events (Singh et al., 1997). A recent study from the Swiss Alps reports a mean contribution of this energy balance component to snowmelt of 13% (Würzer et al., 2016), which is in the same order of magnitude as is found in this study (6%). The ground heat flux, which was not considered in this study, has been shown to provide less than 1% of total energy input and is thus of minor importance during RoS events (Würzer et al., 2016). Finally, it should be noted that the application of physically based snow energy balance models is found to be sensitive to the parameter choice, the model structure, and the forcing error, even when applied at the point scale (Günther et al., 2019). An application of such approaches at the catchment scale is further hampered by the high temporal and spatial variability of input variables and the lack of corresponding measurements at this scale. Results of this study suggest that the chosen parameterization of the energy balance is robust in both time and space, which is seen here as an important advantage compared to the use of more physical energy balance models, particularly when applied to forecast snowmelt several days ahead.

7. Conclusions

For the anticipation of RoS floods in prealpine areas, global forecast models can provide valuable information. By using ECMWF global forecast models as input to a conceptual hydrological model, valuable forecasts of RoS disposition (i.e., minimum rainfall amounts, initial snow cover and meltwater contribution to discharge) can be made and be used as a basis to issue disposition warnings several days ahead of an event. Thereby, forecasts of liquid precipitation and meltwater contribution for distinct catchments are complemented by maps of actual as well as predicted snow accumulation and snowmelt, which may be particularly valuable for a regional assessment of RoS disposition. Calibration of the presented approach using ERA5 as input is found to be suitable to find appropriate parameter sets to be used in the forecast, although we propose to apply lower precipitation amount thresholds to identify RoS events in the forecast as compared to the analysis. Furthermore, a two-stage calibration approach including spatial information of snow cover tackles the problem of equifinality to some point. For operational application, the operational HRES forecast or local measurements could be used as input for the analysis, although the latter will require a recalibration of model parameters. Also, we highlight the potential of ensemble-based forecasts as input to forecast RoS events in future applications.

The forecast of the peak runoff during RoS events was not the aim of this study. For the time being it seems very challenging to forecast—some days in advance—the exact timing and amount of runoff of RoS events. This is not at least because the medium-range forecast of exact timing and amounts of precipitation (including its phase) is still highly uncertain with current weather prediction models.

Finally, results highlight the importance of the continuous modeling of state variables when forecasting RoS events, which could be used as a starting point to the combination of such approaches with scenario-based modeling or event-based flood forecasting at shorter lead times.

Acronyms

ECMWF = European Centre for Medium-Range Weather Forecasts
ENS = Ensemble
ERA5 = ERA5 reanalysis data set
FAO = Food and Agriculture Organization of the United Nations
HRES = High-resolution
IFS = Integrated Forecasting System
MODIS = Moderate-resolution Imaging Spectroradiometer
PET = Potential evapotranspiration
REV = Relative economic value
ROC = Receiver operating characteristic
RoS = Rain-on-snow
SCA = Snow-covered area
SWE = Snow water equivalent
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