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Estimating the snowfall limit in alpine and pre-alpine valleys: A local evaluation of operational approaches

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ABSTRACT

The snowfall limit has important implications for different hazardous processes associated with prolonged or heavy precipitation such as flash floods, rain-on-snow events and freezing precipitation. To increase preparedness and to reduce risk in such situations, early warning systems are frequently used to monitor and predict precipitation events at different temporal and spatial scales. However, in alpine and pre-alpine valleys, the estimation of the snowfall limit remains rather challenging. In this study, we characterize uncertainties related to snowfall limit for different lead times based on local measurements of a vertically pointing micro rain radar (MRR) and a disdrometer in the Zulg valley, Switzerland. Regarding the monitoring, we show that the interpolation of surface temperatures tends to overestimate the altitude of the snowfall limit and can thus lead to highly uncertain estimates of liquid precipitation in the catchment. This bias is much smaller in the Integrated Nowcasting through Comprehensive Analysis (INCA) system, which integrates surface station and remotely sensed data as well as outputs of a numerical weather prediction model. To reduce systematic error, we perform a bias correction based on local MRR measurements and thereby demonstrate the added value of such measurements for the estimation of liquid precipitation in the catchment. Regarding the nowcasting, we show that the INCA system provides good estimates up to 6 h ahead and is thus considered promising for operational hydrological applications. Finally, we explore the medium-range forecasting of precipitation type, especially with respect to rain-on-snow events. We show for a selected case study that the probability for a certain precipitation type in an ensemble-based forecast is more persistent than the respective type in the high-resolution forecast (HRES) of the European Centre for Medium Range Weather Forecasts Integrated Forecasting System (ECMWF IFS). In this case study, the ensemble-based forecast could be used to anticipate such an event up to 7–8 days ahead, whereas the use of the HRES is limited to a lead time of 4–5 days. For the different lead times investigated, we point out possibilities of considering uncertainties in snowfall limit and precipitation type estimates so as to increase preparedness to risk situations.

1. Introduction

The snowfall limit has important implications for different hazardous processes associated with prolonged or heavy precipitation. From a hydrological perspective, the snowfall limit in fact determines the percentage of liquid precipitation in a catchment and therefore exerts control on direct runoff (Tobin et al., 2012), as most precipitation at extra-tropical latitudes is formed from the solid phase (Fabry, 2015). In snow-covered areas, the presence of liquid precipitation is decisive for the occurrence of rain-on-snow events during which runoff can be considerably enhanced by snowmelt (Beniston and Stoffel, 2016; Morán-Tejeda et al., 2016; Würzer et al., 2016). Furthermore, in glaciated catchments, the aggregate state of precipitation at the surface will affect albedo and thus the production of glacial meltwater (Rohrer, 1989). For example, snow and glacial meltwater were relevant for flood generation in the Swiss Alps on 10 October 2011. During this event, the combination of meltwater and long lasting rainfall up to about 3000 m a.s.l. triggered debris flows and floods, which caused damage in the order of 94 million US$ or an equivalent of 71% of all precipitation-induced damage in that year (Andres et al., 2012).

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Characteristics of the snowfall limit are also relevant for the occurrence of freezing precipitation, which is not uncommon during winter months over continental Europe and northern America (Carrière et al., 2000; Cortinas Jr. et al., 2004; Rauber et al., 2001). Freezing rain, i.e. the occurrence of supercooled rain drops falling onto a sub-freezing surface (Forbes et al., 2014), is particularly dangerous because of its ice-loading effects on power wires and potentially catastrophic cascading effects (Call, 2010; Chang et al., 2007). For example, after a prolonged episode of freezing rain in Slovenia in 2014, more than 300 power lines were broken and 25% of Slovenian residents were without electricity, heating and water (Forbes et al., 2014). Most frequently, freezing rain develops ahead of a surface warm front, where snow particles melt in an elevated warm layer and thereafter fall into a sub-freezing, near-surface layer of very cold continental or Arctic air (Forbes et al., 2014; Rauber et al., 2001). Thereby, the depth of the melting layer determines whether the snow particles melt completely and turn into freezing rain, or whether they melt only partly and eventually refreeze to ice pellets until they reach the ground surface (Forbes et al., 2014; Reeves et al., 2014).

The snowfall limit can be estimated by operational approaches for different lead times, but its estimation remains challenging, especially in mountainous terrain (Schauwecker et al., 2016; Tobin et al., 2012). For hydrological applications, the snowfall limit is often estimated by an inter- and extrapolation of surface temperature measurements (Tobin et al., 2012). In those cases where temperature measurements are available within the catchment, extrapolations to higher and lower elevations are realized by assuming a constant lapse rate, which has been shown to be subject to considerable uncertainties (Schauwecker et al., 2016). If temperature measurements are, by contrast, not available within a catchment, a spatial interpolation approach is usually applied to more distant observations (Viviroli et al., 2009). In mountainous terrain, however, where the snowfall limit can be highly dynamic, such procedures will inevitably introduce additional uncertainty. In the case of steep valleys, the snowfall limit can be lowered locally by the cooling of the air during a single precipitation event (Unterstrasser and Zängl, 2006), a phenomenon which can hardly be predicted from distant observations. As an alternative to temperature inter- and extrapolation, the snowfall limit can also be inferred from radar observations, as they can detect falling hydrometeors directly and thus estimate their type from polarimetric properties of the radar signal (Chandrasekar et al., 2013; Ryzhkov and Zrnic, 1998). While such approaches have been shown to work well for stratiform precipitation over flat areas, they still suffer from limitations in the case of convective precipitation or if the radar signal is blocked by mountain topography at lower elevations (Besic et al., 2016). To predict the snowfall limit and precipitation type with a certain lead time, numerical weather prediction models are used; these are available for different temporal and spatial scales (Alfieri et al., 2012). However, direct outputs of such models may be of limited use for flood forecasting in steep terrain and in deep, narrow valleys, where model topography remains coarse and thus differs too much from actual conditions. Even worse so, in these areas, the height range with mixed precipitation can be broader than over flat areas under certain conditions (Haiden et al., 2011).

The accurate identification and forecast of freezing precipitation continues to be a substantial challenge for numerical weather prediction models (Forbes et al., 2014; Reeves et al., 2014). Recent improvements in the high resolution model (HRES) of the European Centre for Medium-Range Weather Forecast Integrated Forecasting System (ECMWF IFS) include a more representative timescale for the refreezing of rain drops, which is expected to improve the distinction between ice pellets and freezing rain (Forbes et al., 2014). Nonetheless, the generation of freezing drizzle drops from supercooled water in the absence of a warm melting layer is not yet represented in this system (Forbes et al., 2014). A detailed analysis of such an event and implications for the prediction of similar events can be found in Fernández-González et al. (2014, 2015). Also, more experience needs to be gained with ensemble forecasts (ENS) of precipitation type, which are expected to increase the accuracy of mixed precipitation and in particular freezing rain forecasts (Forbes et al., 2014; Gascón et al., 2018).

Therefore, the aim of this study is to evaluate operational approaches estimating the snowfall limit and precipitation type for different lead times at the local scale. Thereby, we investigate the performance of temperature interpolation approaches as well as weather prediction from ECMWF IFS at different temporal and spatial scales in the Zulg valley, Switzerland. Resulting estimates are compared to measurements of a vertically pointing micro rain radar (MRR) and a disdrometer, which provide local information about these quantities at high temporal resolution. For the different lead times considered, the following questions are addressed:

1. Monitoring: How do temperature interpolation approaches compare with analyses of the Integrated Nowcasting through Comprehensive Analysis (INCA) system and how relevant are related uncertainties for hydrological applications?
2. Nowcasting: How uncertain are predictions by the INCA system with steadily increasing lead times up to 6 h?
3. Medium-range forecasting: How does the HRES compare to an ENS forecast of the ECMWF IFS for a selected case study?

The paper is organized as follows: In Section 2, the study area is described and typical seasonal patterns of the snowfall limit are shown. In Section 3, available data and methods to estimate both the snowfall limit and related uncertainties are outlined. Results are presented in Section 4 and discussed in Section 5. Finally, conclusions with respect to operational monitoring and prediction of the snowfall limit are drawn in Section 6.

2. Study area

Operational approaches to estimate the snowfall limit are evaluated in the Zulg valley, Switzerland (Fig. 1). The Zulg catchment is 89 km^2 large and reaches from the confluence of the Zulg and the Aare river at 550 m a.s.l. to elevations up to 2060 m a.s.l. The bulk of the catchment (71% of the catchment area) is located between 800 and 1400 m a.s.l. After the confluence of three steep mountain torrents at 1030 m a.s.l., the Zulg descends to the outlet with a rather gentle mean slope gradient of 3%.

Estimation of the snowfall limit in this area is most relevant for hydrological applications during those periods of the year for which it is located within the elevational range of the catchment. The hypsography of the Zulg catchment is shown in Fig. 2 along with a climatology of the freezing level height at Payerne (see Fig. 3 for the location of Payerne), the latter being located typically 300–400 m above the snowfall limit (Fabry and Zawadzki, 1995). Between mid-April and mid-November, the median freezing level height is located above the highest mountain peaks of the Zulg valley. During this period, precipitation in the catchment can be assumed to fall predominantly in the liquid state. However, the freezing level height can strongly deviate from its climatological median. For example, a few days before the flood event in October 2011, it was located 1000–1500 m below its median, favouring conditions for a rain-on-snow event on 10 October 2011. Considering the 5th and the 95th percentile of observed freezing level heights, an accurate estimation of the snowfall limit in the Zulg valley is already important from the beginning of October and until the end of May. During this period, the snowfall limit can be located within the elevational range of the catchment and will thus determine whether most of the precipitation is falling in its solid or in the liquid state.

3. Data and methods

The operational approaches applied to estimate the snowfall limit in