



# Rain-on-snow events, floods and climate change in the Alps: Events may increase with warming up to 4 °C and decrease thereafter



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## HIGHLIGHTS

- Rain on snow events are major drivers of Alpine flood events
- Future trends show that the rain-on-snow events may increase as a first response to sustained warming but decline thereafter
- Enhanced flood risks as temperatures warm up to 4°C will impact natural and socio-economic systems more than today

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## ABSTRACT

This paper focuses on the influence of mountain rain-on-snow (ROS) events that can on occasion trigger major floods in alpine catchments. In order to assess the evolution of these events in a recent past, and the potential changes that could be experienced in a changing climate over coming decades, we have focused on a small catchment in north-eastern Switzerland, the Sitter, well-endowed with both climate and hydrological data. Observations show that there has been an increase in the number of rain-on-snow events since the early 1960s related to the rise in atmospheric temperatures. Results from a simple temperature-based snow model show that the number of ROS events could increase by close to 50% with temperatures 2–4 °C warmer than today, before declining when temperatures go beyond 4 °C. The likelihood of more ROS events suggests that the risks of flooding in a future climate may indeed get worse before they improve.

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## 1. Introduction

Extreme rainstorms in headwater catchments may trigger torrential and river floods, debris floods or debris flows (Borga et al., 2014). Floods in mountain areas typically are the result of high surface runoff levels that exceed the carrying capacity of hydrological systems. In addition, critical situations for floods in mountains are often accompanied by other high-risk events, such as landslides, debris flows, and other slope instability phenomena (Stoffel and Huggel, 2012; Borga et al., 2014; Stoffel et al., 2014a) which can favor the occurrence of process chains (Allen et al., 2016) or amplify the negative effects of the flood phenomenon itself. In the Alps, a substantial number of large floods has been recorded over the last 30 years, causing several billion Euros in damage costs and loss of life, despite increasingly advanced levels of civil protection and early warning. As a consequence, improved understanding of the hydrogeomorphic response of slopes and channel systems to various types of extreme rainfalls is thus a key to identifying the impacts of climate change on flood occurrence and magnitude (Harvey, 2007).

In many parts of the Swiss Alps, much of the heavy precipitation that can trigger floods and collateral hazards occurs towards the end of the summer and into the early fall (e.g., Beniston, 2006; Stoffel and Beniston, 2006; Stoffel et al., 2014b). During this seasonal transition, synoptic weather patterns are favorable to substantial moisture convergence into the Alpine domain. This humidity is forced to rise above the topography and can produce either periods of short but intense rainfall, sometimes exceeding 100 mm/day or continuous, moderate precipitation lasting several days. In both instances, the amount of precipitation can on occasion be sufficient to generate catastrophic floods (Bezzola et al., 2008).

Another trigger mechanism for floods in mountains such as the Swiss Alps is related to liquid precipitation that falls on a pre-existing snowpack, referred to as rain-on-snow (ROS). According to temperature and the amount of rainwater falling onto snow, large volumes of snow can melt rapidly and in some situations generate considerable fluxes of water in a catchment zone. Flood hazards that might be sub-critical during an event where precipitation falls on a snow-free surface may thus cross the critical threshold when snowmelt is added to rainfall.

Due to the topographic characteristics of Switzerland, floods are recurrent as exemplified by the recent flood episodes in May 1999, August

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2005, October 2011 and summer 2014 on the Swiss plateau, where rivers flooded several major cities (Bezzola et al., 2008; Hilker et al., 2009). The 1999 and 2011 floods are in fact classical examples of ROS-triggered floods where intense rainfall during elevated temperatures (high freezing levels) fell on a pre-existing snowpack (Rössler et al., 2014). In the first days of May 2015, the City of Geneva encountered its first-ever urban flooding in the University district along the Arve River. This exceptional event was linked to an intense rainfall event that occurred under very mild conditions in the Mont-Blanc region, with the zero-degree isotherm well above 3000 m, and fell on a thick snowpack in the mountains. The discharge in the Arve River, normally around 75 m<sup>3</sup>/s in the urban zone, exceeded 900 m<sup>3</sup>/s during the flood event. Further to the east, communities at the foot of the mountains on the banks of Lake Geneva suffered from multiple debris-flows resulting in high damage costs to infrastructure.

In this paper, we shall focus on a small catchment in the north-eastern Swiss Alps, the Sitter, which has been monitored for over 50 years. Following a summary of the observed characteristics of discharge, climate, and ROS events in the region since the 1960s, we shall explore, using a simple snow model, possible changes in ROS under different incremental temperature increases coupled to changes in precipitation. The results that will be discussed here suggest that ROS events may actually increase under warmer temperatures at high elevations; and that only when wintertime temperatures exceed 5 °C beyond the current baseline does the risk of ROS events significantly decline.

There have been other recent studies focusing on ROS, for example Surfleet and Tullos (2013) for a catchment in the mountains of Oregon (Western United States) or Moran Tejada et al. (2016, under review) focusing on the Swiss Alps. The former study looks at the return periods of ROS events in a historic perspective and also for two of the Intergovernmental Panel on Climate Change (IPCC, 2013) greenhouse-gas emission scenarios, whereas the latter investigates essentially the statistics of ROS at various locations but with no assessment of the potential for flood situations. The approaches discussed in this paper enable to focus on a finer perspective in terms of incremental temperature changes that put into evidence the fact that ROS events may first increase with rising temperatures before declining if warming continues beyond 4 or 5 °C. The possible behavior of ROS episodes as described below, and the

implications for floods in small catchments, provides a finer view of these processes compared to other papers addressing ROS.

### 1.1. Case-study area, data, methods

The Sitter River catchment originates in the Alpstein massif of the Canton of Appenzell in the north-eastern part of Switzerland (Fig. 1). The catchment covers a surface area of 340 km<sup>2</sup>, with a maximum elevation of 2502 m above sea level (Säntis) and the lowest elevation around 470 m where the Sitter joins the Thur River (a tributary of the Rhine). The catchment is endowed with a hydrological gauge station located in Appenzell and two of the Swiss weather service ([www.meteoswiss.ch](http://www.meteoswiss.ch)) climate recording stations close to the upper and lower extremities of the catchment (Säntis, 2502 m; St Gallen, 776 m). This has enabled us to use daily weather (maximum and minimum temperature,  $T_{\max}$ ,  $T_{\min}$ , in °C; daily precipitation,  $P$ , in mm; and snowpack thickness,  $S_{\text{NH}}$ , in cm) and daily discharge ( $Q$  in m<sup>3</sup>/s) data from 1960 to 2015. Average daily discharge in the upper catchment during the period of record is 3.5 m<sup>3</sup>/s, while the maximum daily value of 58.6 was observed on May 12, 1999. This was one of the most intense ROS events recorded since the 1950s, with heavy precipitation exceeding 70 mm falling in mild conditions on a deep snowpack up to 2500 m altitude (FOEN, 2000).

In order to investigate the possible changes in the frequency of ROS events under different climate conditions compared to the observed 1960–2015 baseline, we applied an empirical snow model (snowMAUS) developed by Trnka et al. (2010) for application to zones where detailed climate data (beyond temperature and precipitation) may not be available (e.g., radiation parameters, low-level atmospheric dynamics, or other parameters that can also influence snow accumulation and snowmelt). The model relies on just three variables –  $T_{\min}$ ,  $T_{\max}$  and  $P$  – to describe snow accumulation and ablation, using empirically-derived thresholds which determine whether accumulation, melt and sublimation may occur, and at what rate. The set of equations presented by Trnka et al. (2010) read:

For Snow Accumulation:

$$\text{If } T_{\min} \leq T_{\min \text{ Accu2}} \text{ then Snow Accum} = \text{Precip} \quad (1)$$

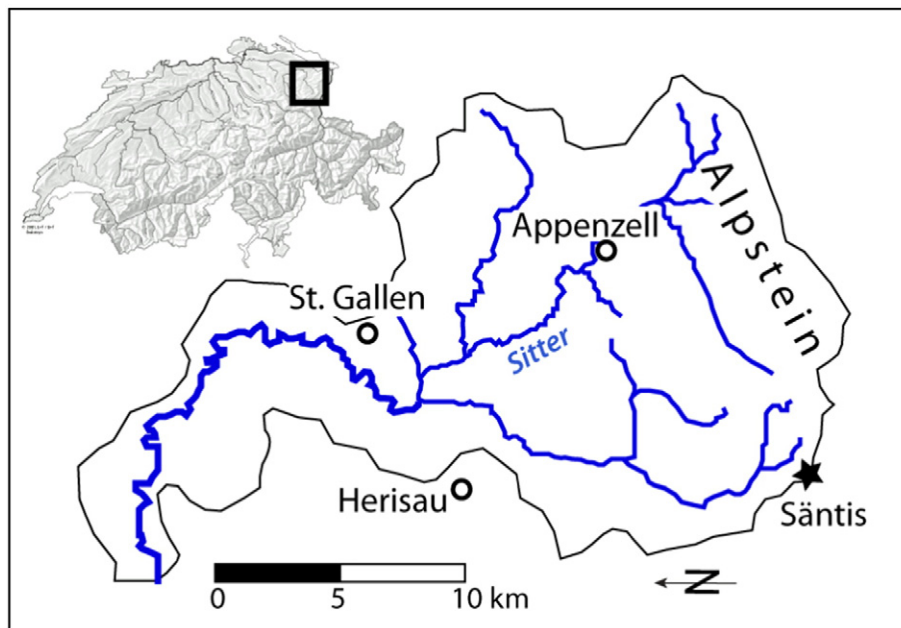


Fig. 1. Map of Switzerland showing the location of the Sitter Catchment. The climate recording stations are located at St Gallen (776 m above sea-level) and Säntis (2502 m above sea-level), and the hydrological gauge station is at Appenzell.

If  $T_{min} \geq T_{min\ Accu1}$  then  $Snow\ Accum = 0$  (2)

If  $T_{min\ Accu2} < T_{min} < T_{min\ Accu1}$  then :  
 $Snow\ Accum = (1 - (T_{min} - T_{min\ Accu2}) / (T_{min\ Accu1} - T_{min\ Accu2})) \times Precip$  (3)

$T_{min\ Accu1}$  is a value of temperature below which part of the precipitation is assumed to fall as snow, while  $T_{min\ Accu2}$  is a threshold below which all precipitation will fall as snow. As for the parameters used in the original paper (Trnka et al., 2010), the values of  $T_{min\ Accu1}$  (0 °C) and  $T_{min\ Accu2}$  (-6 °C) are seen to work well here. This is not surprising, since the snoMAUS model has been extensively calibrated for sites in

the Austrian Alps, whose altitudinal characteristics are very similar to those in the Sitter Catchment.

For Snow Melt:

Snow melt processes are driven by critical  $T_{min}$  and  $T_{max}$  thresholds above which snow-melt occurs, with or without precipitation. This yields the following relationships:

If  $T_{min} < T_{min\ Crit}$  then  $Snow\ Melt = 0$  (4)

If  $T_{min} \leq 0$  and  $T_{max} < T_{max\ Crit}$  then  $Snow\ Melt = 0$  (5)

If  $T_{min} \geq T_{min\ Crit}$  and If  $T_{max} \geq T_{min\ Crit}$  then  $Snow\ Melt = (T_{min} + T_{min\ Crit}) \times r_{melt}$  (6)

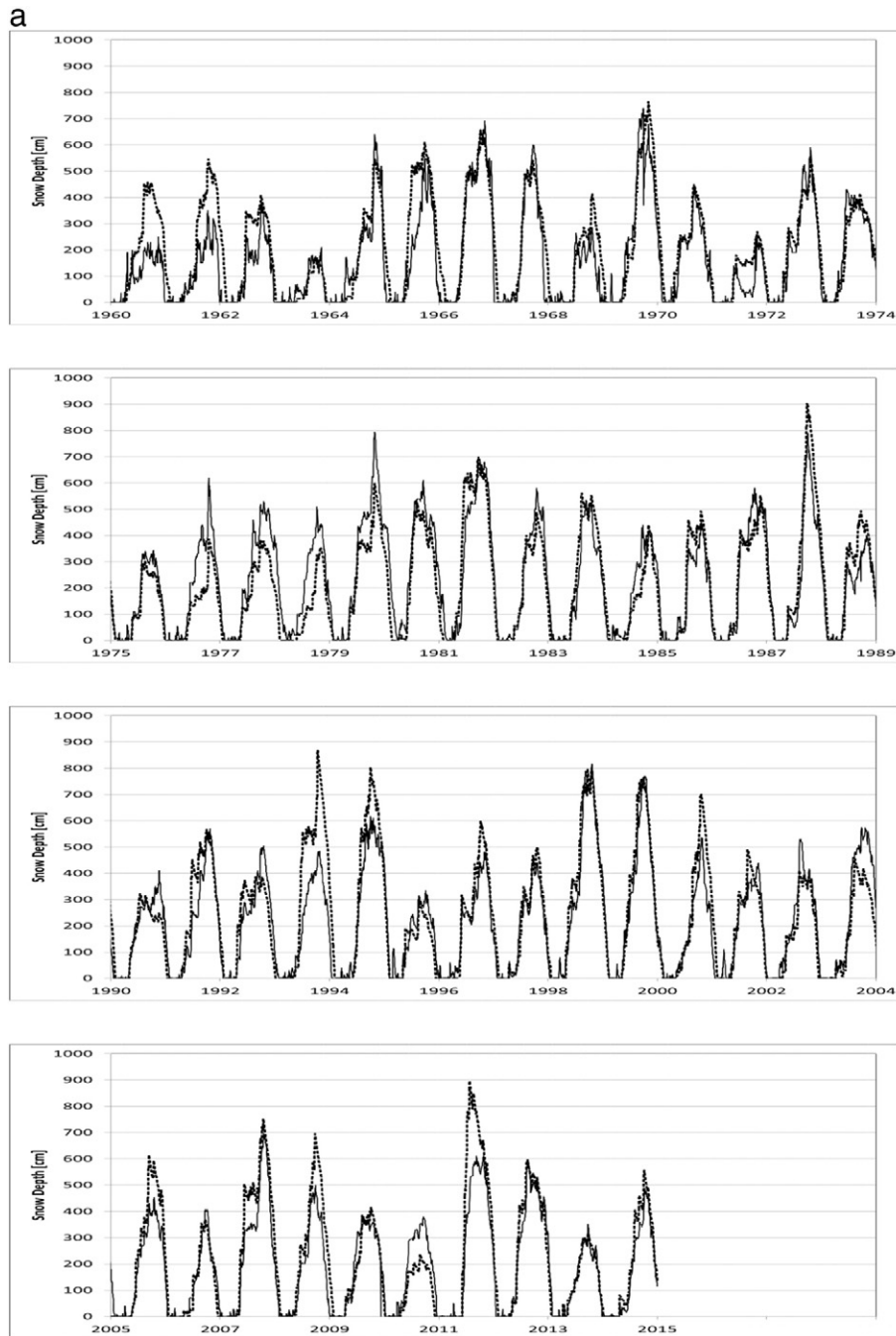


Fig. 2. a: Observed (solid line) and simulated (dashed line) snow depths for the period 1996–2015 at Sântis, located at 2502 m above sea level, for 15-year segments from 1960 (top frame) to 2015 (bottom frame) b: Observed (solid line) and simulated (dashed line) snow depths for the period 1996–2015 at St. Gallen, located at 776 m above sea level, for 15-year segments from 1960 (top frame) to 2015 (bottom frame).

where  $r_{melt}$  (mm/°C/day) is a coefficient that takes into account the melting rate in mm of snow water equivalent when temperatures are above the critical thresholds. While Equation 6 is only temperature-dependent and thus does not explicitly take into the fact that liquid water falling on a pre-existing snowpack could contribute to even more enhanced snow-melt than just temperature, the rather good correspondence between our simulations and observations suggest that temperature nevertheless remains the dominant driving factor for snow melt.

For the critical  $T_{min}$  and  $T_{max}$  values, we found for the best fits (see Fig. 2 and Table 1 below) that the values suggested by Trnka et al. (2010), respectively  $-12\text{ °C}$  and  $+5\text{ °C}$ , perform well in the case of both St Gallen and Saentis. Our value for  $r_{melt}$ , 0.40, is also very close to the 0.42 used by the snoMAUS model for Austria. Finally, the snoMAUS model also enables an estimate of sublimation (as a fixed

loss of snow water equivalent) for days where snow cover is present on the ground above a fixed value of snow water equivalent – 20 mm – where sublimation can be expected to occur. The snow water equivalent (in mm) on a particular day  $n$  is thus computed as:

$$\text{If } 0 < \text{Snow}_{n-1} \leq SC_{\text{threshold}} \text{ then } \text{Snow}_n = \text{Snow}_{n-1} + (\text{Snow Accum} - \text{Snow Melt}) \tag{7}$$

$$\text{If } \text{Snow}_{n-1} > SC_{\text{threshold}} \text{ then } \text{Snow}_n = \text{Snow}_{n-1} + (\text{Snow Accum} - \text{Snow Melt} - \text{Sublim}) \tag{8}$$

The collective set of Eqs. (1)–(8) thus enables in a rather simple manner to take into account snow accumulation and melt processes in the presence of both solid and liquid precipitation – and hence ROS events can be reasonably well simulated.

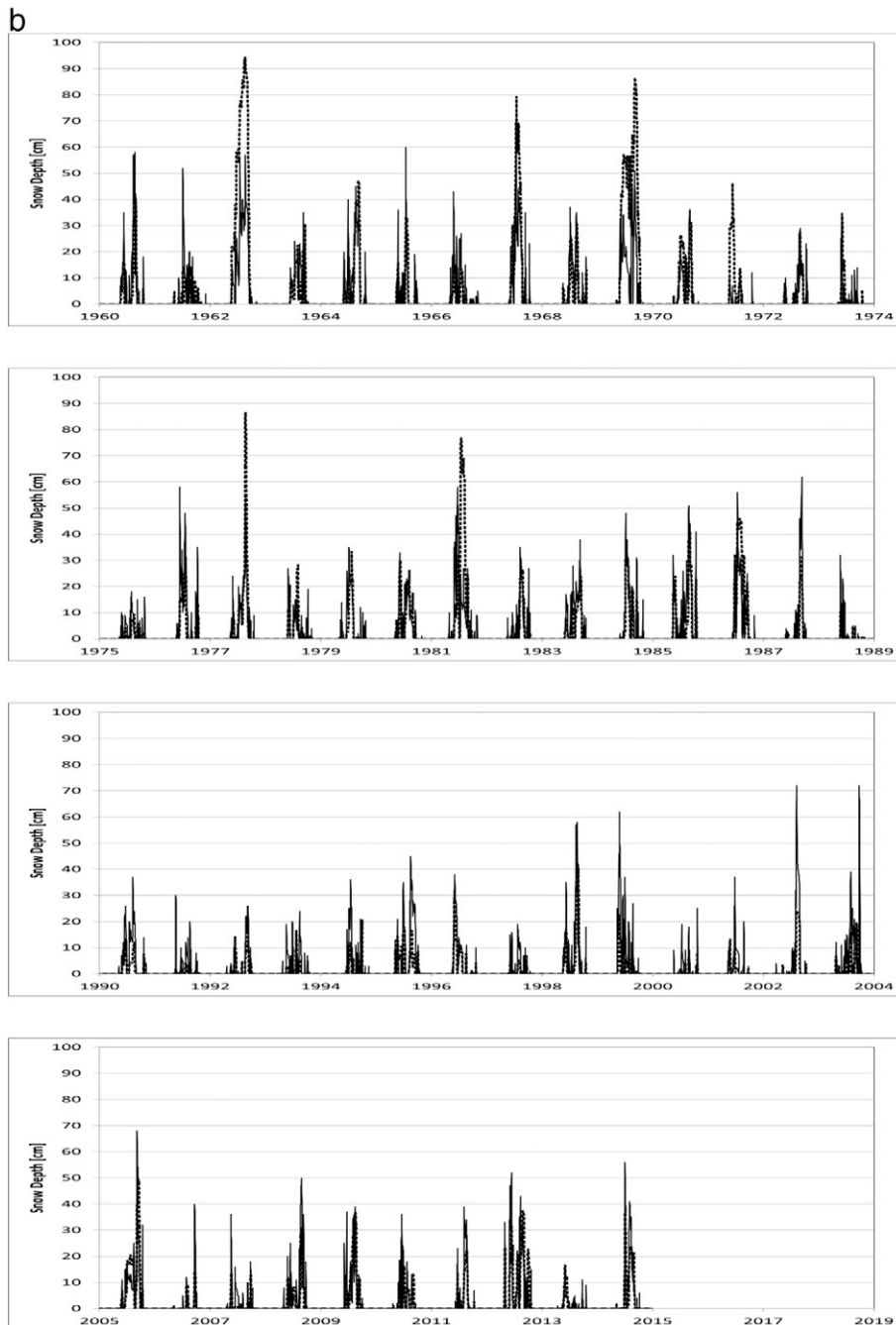


Fig. 2 (continued).

Fig. 2 compares the cycle of the observed winter snowpack behavior and the seasonal snow accumulation/melt simulated by the snowMAUS model at the Säntis (Fig. 2a) and St Gallen (Fig. 2b) weather stations for the last 20 years. Averaged over the 55 years of record, the snowMAUS model slightly overestimates both the total accumulation and the maximum snow depth by about 5%. For some winters, the goodness-of-fit between simulation and observation is excellent, as for the 1998/1999 or 2012/2013 winters, for example, suggesting that temperature and precipitation in these years are indeed the dominant variables influencing snow amount and duration.

Table 1 provides some information as to the mean, standard deviation and correlations between the observed snow depths averaged over the 55 winters and the model-simulated winters. For both locations, the agreement is good (as already seen in the time series of Fig. 2). The higher-altitude statistics are more robust because of the lower variability associated with a snowpack that is obviously far deeper, less intermittent, and of longer duration than at the lower elevation of St Gallen.

In order to assess possible changes in the frequency of ROS events in a future greenhouse climate, we have used the snowMAUS model to simulate changes in snowpack behavior for a combination of temperature increases ranging from a moderate +1 °C to an extreme +15 °C beyond the observed baseline climate. These changes in temperatures correspond roughly to a conservative RCP scenario (Representative Concentration Pathway, i.e., the greenhouse-gas emission scenarios developed by the Intergovernmental Panel on Climate Change; IPCC, 2013), namely the RCP2.6 scenario by 2050 and a rather pessimistic RCP8.5 scenario by 2100, with associated uncertainties. It is to be noted that large departures from mean climate conditions by >15 °C have occurred in some recent winters (Beniston, 2005) such that the simulations conducted here could represent not only a future, sustained change in climate, but also an isolated and unusually mild winter. For the shifts in precipitation, we assumed 0.8, 1.0, and 1.2 times the current values for the winter half-year, which is in line with recent Alpine climate scenarios (e.g., Gobiet et al., 2014). The  $\Delta T$  and  $\Delta P$  values have been added to each daily value of  $T_{min}$ ,  $T_{max}$  and precipitation, respectively, for the 55 years of record, in order to generate a long time-series with systematically warmer, and drier or wetter, conditions than those observed between 1960 and 2015. These simulation experiments are representative of some of the more extreme-warm winters that have been observed in a recent past (e.g., Beniston, 2012) and that are likely to become increasingly common with the projected rise of mean annual and seasonal temperatures (IPCC, 2013).

## 2. Results and discussion

### 2.1. Example of ROS events: the 1998/1999 season

In order to identify rain-on-snow (ROS) events, we have determined episodes during which above-zero  $T_{min}$  and  $T_{max}$  allow precipitation to fall in its liquid form on a pre-existing snowpack. This exercise has been achieved for fixed altitudes of 1000, 1500, 2000, and 2500 m above sea level within the upper Sitter catchment where ROS events are most significant under current conditions. We tested different thresholds of precipitation during ROS periods, namely 10 mm/day, 25 mm/day and 50 mm/day, and we have seen from the observations that most of the flood episodes in this catchment have occurred during ROS for rain thresholds beyond 50 mm/day. We thus conclude that this threshold represents a critical level beyond which flood potential becomes significant.

**Table 1**  
snowMAUS model statistics for the 55 years of record (1960–2015) at Saentis and St Gallen.

	Observed (cm)	Simulated (cm)	% difference	Correl coeff
<b>Saentis</b>				
Snow depth (mean 55 years)	243.4	263.3	108.1	0.85
Maximum snow depth (mean 55 years)	508.2	509.6	100.3	0.91
Snow depth (standard deviation)	180.9	173.2	95.7	
Maximum snow depth (standard deviation)	144.2	146.5	101.6	
<b>St Gallen</b>				
Snow depth (mean 55 years)	13.9	12.4	89.3	0.73
Maximum snow depth (mean 55 years)	40.4	31.9	78.9	0.53
Snow depth (standard deviation)	11.8	16.5	139.8	
Maximum snow depth (standard deviation)	16.2	21.3	131.5	

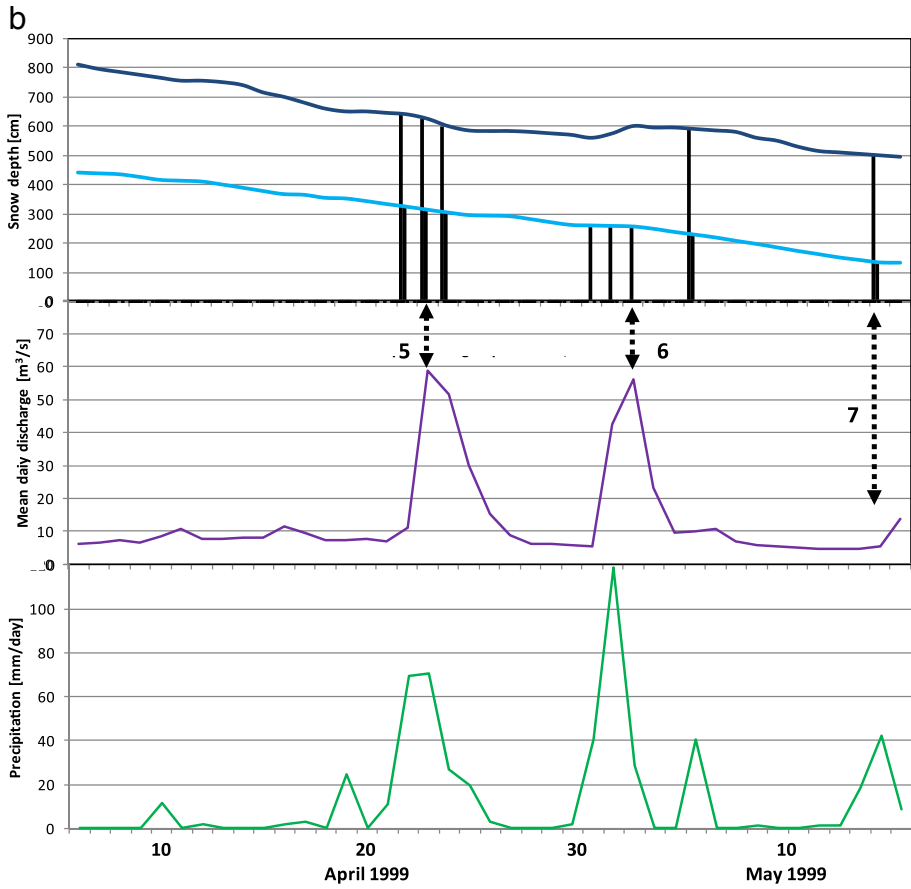
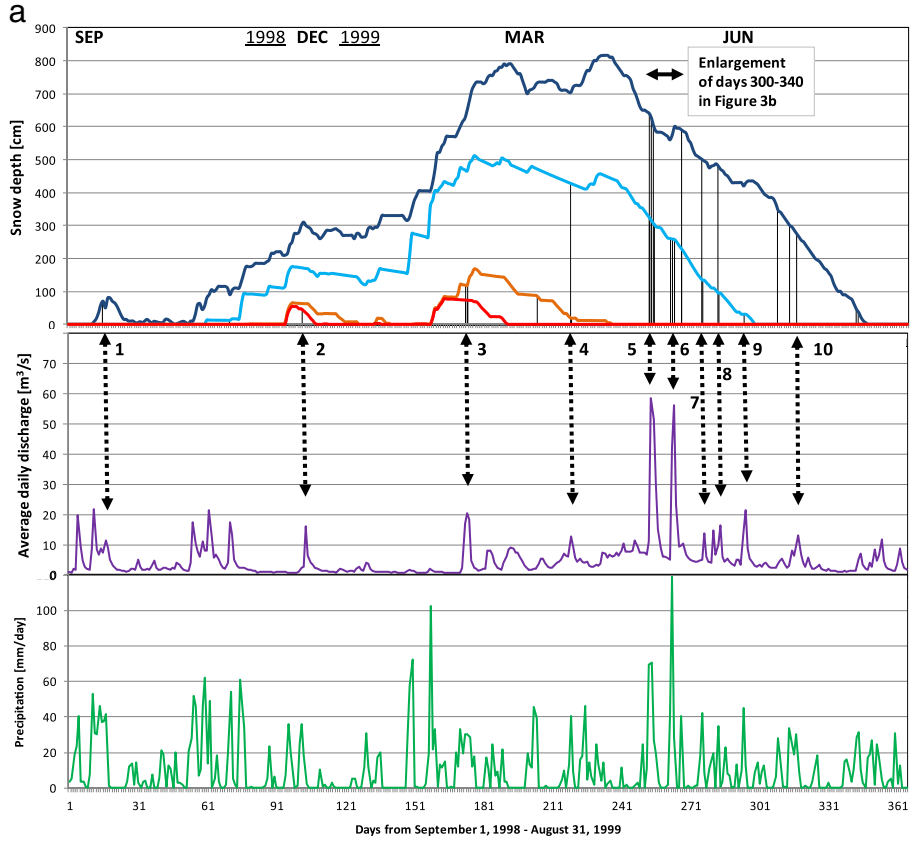
Fig. 3 provides an overview of an annual cycle centered on the winter of 1998/1999 (i.e., from September 1, 1998–August 31, 1999), using the climate data from the Säntis and St Gallen sites, and simulated by the snowMAUS model for the intermediate altitudes (1000, 1500 and 2000 m). Temperature and precipitation data have been linearly interpolated between the Säntis and St Gallen weather stations and the simple snow model has been applied at the intermediate altitudes using the interpolated temperature and precipitation data to provide the snow duration and snow thickness profiles portrayed in Fig. 3. The three panels show the snow profiles with the ROS events at different elevations, the Sitter River discharge, and the daily precipitation in the lowest panel. Fig. 3b is an enlargement of the period of peak discharge, centered around April and early May of 1999.

The vertical lines that intercept the snowpack curves pinpoint the days on which the simultaneous temperature, precipitation and snowpack criteria for ROS events are satisfied. Finally, the lower panel shows the daily discharge values of the Sitter River measured at the gauge station located in the upper part of the catchment. This segment of the river is mostly unregulated and hence the discharge represents the Sitter's "natural" response to upstream precipitation and snowpack behavior.

The ROS events for the lower altitude snowpack occur early in the season (see events labeled 2 and 3 in Fig. 3), while for higher-level snowpack there is a far larger number of events that take place mostly during the late spring and early summer (events given as 5–10 in Fig. 2). Of the 21 ROS events for the season 1998/1999, only 3 occur between December and February, whereas 12 events occur between mid-May and late June, when days are longer, the snowpack is well into its end-of-season melting phase, and the likelihood of rainfall rather than snow is greater at almost all elevations. The influence of altitude can be seen when inspecting specific events such as those labeled 4, 6, and 9, where rain falls onto snow up to 2000 m but not at the highest levels of the Sitter catchment because temperature conditions there are favorable to snowfall rather than rain. In events 4 and 6, the buildup of the snowpack at 2500 m is clearly seen, while at 2000 m the snowpack thickness simultaneously diminishes. Other events such as 5, 7, or 8 mark periods for which ROS conditions are fulfilled at all altitudes containing snow at the start of the rainfall episode.

The response of the Sitter River to the ROS events, seen in the middle frame of Fig. 3, is almost immediate or takes place within 24 hours. While not every increase in discharge by the Sitter is the result of a

**Fig. 3.** a: Upper panel: Snow depth in the Sitter River catchment for the winter 1998/1999, for 4 altitudes: 2500 m (dark blue line); 2000 m, (light blue), 1500 m (orange) and 1000 m above sea level (red). Vertical bars indicate ROS events with  $P > 50$  mm/day. Middle panel, purple line: Average daily discharge of the Sitter River. Dashed, numbered arrows emphasize the coincidence between ROS occurrence and the increase in runoff that can range from 4 to 16 times the daily average discharge. Lower panel, green line: Daily precipitation totals b: As panel a, except for an enlarged window focusing on episodes 5, 6, and 7 in April and May 1999.



ROS episode (e.g., the first two peaks prior to event 1 or those around day 61), most of the more significant, short-lived increases are directly linked to ROS episodes. Indeed, two-thirds of the daily average flows ( $Q$ ) beyond  $10 \text{ m}^3/\text{s}$  are related to ROS episodes, and all flows above  $20 \text{ m}^3/\text{s}$  are invariably triggered by ROS events. The highest daily discharges recorded over the period covered in this study are in fact related to very heavy precipitation (over  $70 \text{ mm}/\text{day}$ ) falling on snow up to the highest levels at Säntis (episode 5), and are accompanied by  $> 110 \text{ mm}/\text{day}$  falling on a snowpack up to the  $2000 \text{ m}$  level. The Sitter responds with a daily-average discharge of  $58.6 \text{ m}^3/\text{s}$  and  $56.2 \text{ m}^3/\text{s}$  for episodes 5 and 6, respectively. While the precipitation amount was slightly higher for the latter event, the snowmelt contribution to runoff was substantially greater during episode 5.

Working with daily-mean values unfortunately overshadows the fact that momentary peak discharges (from a few minutes to a few hours) are much greater, especially in the case of flashy peak flows (Borga et al., 2007, 2008), and that it is those very high flows that can cause substantial problems and major threats to people and infrastructure. For event 5, for instance, Sitter runoff had exceeded  $80 \text{ m}^3/\text{s}$  for over an hour on May 12, peaking at  $88.7 \text{ m}^3/\text{s}$ , while on May 22, the event exceeds  $80 \text{ m}^3/\text{s}$  for 7 h, peaking at  $101.6 \text{ m}^3/\text{s}$ . Both these episodes led to downstream flooding, not only along the Sitter itself but also in the other rivers flowing towards the Lake of Constance (which itself reached record-high, critical levels in this time frame) and the Rhine River (FOEN, 2000). As a general rule, the peak-over-average ratio ranges from 1.4–1.8 for the discharge levels beyond the  $25 \text{ m}^3/\text{s}$  threshold identified in the 55-year time series.

## 2.2. ROS events in time and space

Fig. 4 provides, in the form of Hovmoeller-type diagrams, an overview of the timing of each ROS event during the 1960–2015 record, beyond a threshold of  $50 \text{ mm}/\text{day}$ , observed at Säntis and interpolated using the St Gallen data and the snoMAUS model for the  $1000 \text{ m}$  level. In addition, runoff levels in the Sitter River for  $Q > 50 \text{ m}^3/\text{s}$  (daily average), at the  $1000 \text{ m}$  altitude (upper) and  $2500 \text{ m}$  (lower) are indicated by an X symbol.

The influence of the progressive warming of atmospheric conditions in the region since the 1960s is apparent in the lower elevations, particularly since the 1980s. Prior to this period, there were almost no occurrences of ROS in the middle of the winter, whereas since the mid-1980s, ROS events frequently occur in all winter months. After 2005, there are almost no ROS events in July and August since there is no longer any snow on the ground as could occur in shaded areas up to the middle of the first decade of the 21st century.

Comparing the first and last decades of the observational record, the number of ROS events at  $1000 \text{ m}$  has increased from 23 to 32 events, which represents, in just over half a century, a 40% increase of events which can lead to flood situations. This is indeed mostly related to the increase in the number of winter days during which rain can fall on a preexisting snowpack. At the high elevation site, the number of ROS events has more than doubled from 4 to 9 between the two decades. However, there are no significant changes in the months during which ROS episodes are recorded, i.e., essentially the shoulder seasons between winter and summer in May–June and July–September.

## 2.3. Contribution of snow-melt to total water input during ROS events

We have calculated the precipitation, runoff, and snow-melt conditions during ROS events for different precipitation thresholds, as well as the corresponding figures for precipitation events under snow-free conditions (i.e., in the absence of snow-melt).

We have computed conditions of these parameters for all ROS events, those where ROS periods and  $Q$  beyond a given threshold coincide, and for snow-free (summer) conditions. Results show that during periods of heavy rainfall, beyond  $50 \text{ mm}/\text{day}$ , the response of the Sitter

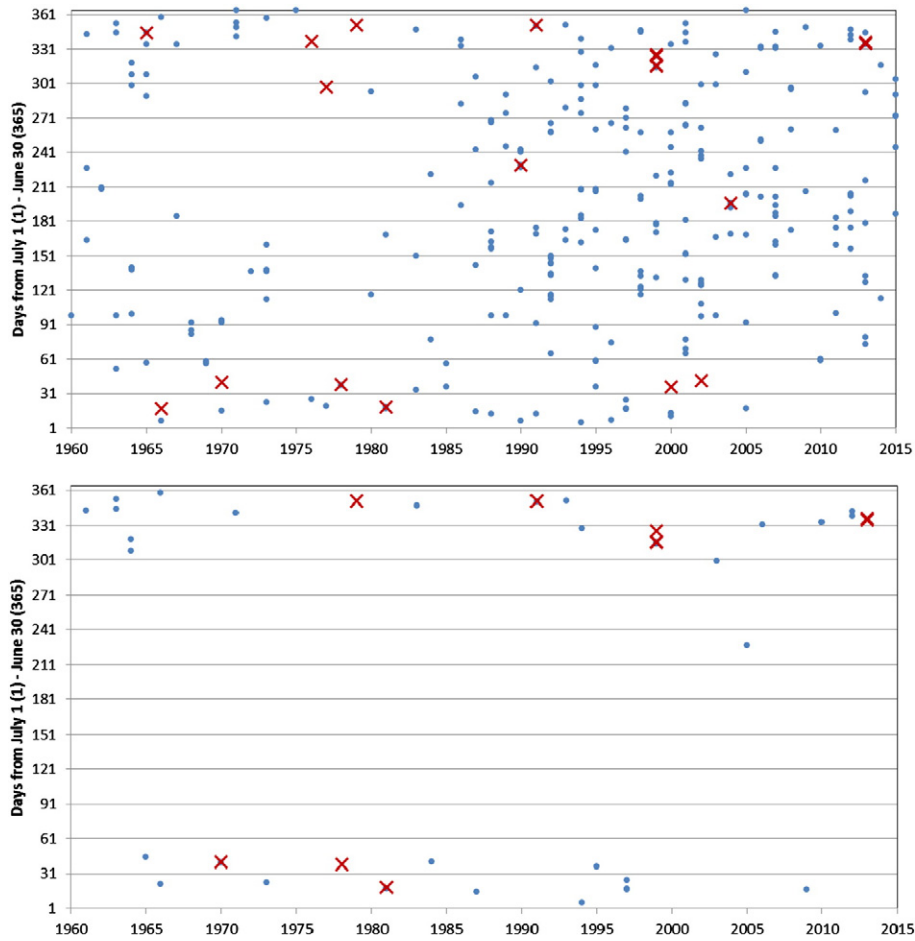
River is clearly greater for ROS events, on average by more than a factor of 3 ( $32.3 \text{ m}^3/\text{s}$  as opposed to just  $9.9 \text{ m}^3/\text{s}$ ). While the average precipitation during such events is perhaps 30% greater than for non-ROS events ( $94.7 \text{ mm}/\text{day}$  vs  $70.7 \text{ mm}/\text{day}$ ), this increase in rainfall alone does not explain the large difference in discharge during heavy precipitation ROS versus non-ROS episodes. The large additional influx of water must come from the melting of the snowpack that represents  $> 12 \text{ cm}$  on average during ROS. Although there are no estimates of snow density from the available data, we can use the approach developed by Jonas et al. (2009) to calculate snow water equivalent (SWE) by applying an average snow density of  $250 \text{ kg}/\text{m}^2$  that has been determined for this elevation in the Swiss Alps. The  $12 \text{ cm}$  of reduction in snowpack yields  $40 \text{ mm}$  of SWE during ROS events. When added on to the average precipitation per event, the total amount of water potentially available for contributing to strong discharge exceeds  $130 \text{ mm}$  of water, i.e., almost double the water available from rainfall alone during non-ROS events. In addition, and in the presence of (melting) snow, soils will be saturated and contribute to immediate runoff, whereas liquid precipitation during a summer event and under snow-free conditions might be absorbed partially by soils.

It is this combination of high rainfall and considerable snowpack ablation that has resulted in 9 of the more critical discharge situations since the 1960s. Indeed, as seen in Fig. 4, 8 of the 10 high-discharge events, leading in some instances to floods, are related to rain falling on snow at  $1000 \text{ m}$ , and 6 out of 10 are linked to rain falling on snow at  $2500 \text{ m}$  altitude. The two high-discharge events not related to ROS are associated with summertime heavy rain (likely thunderstorms) on August 10, 1970 ( $P = 58.8 \text{ mm}/\text{day}$ ), and on June 17, 1979 ( $P = 54.2 \text{ mm}/\text{day}$ ). During this latter event, over  $40 \text{ cm}$  of snow accumulated at the higher elevations in the Säntis massif, but most of the snow beneath an altitude of  $2000 \text{ m}$  had already melted. As a consequence, the rain that was occurring below an elevation of around  $2000 \text{ m}$  did not fall upon any pre-existing snowpack anymore.

## 2.4. A look to possible futures: shifts in the frequency of ROS under changing temperature and precipitation regimes

Fig. 5 shows possible changes in the number of ROS events in the Sitter catchment, for increases in temperature beyond the baseline climate but for the same levels of precipitation as in the baseline, for altitudes ranging from  $1000$  to  $2500 \text{ m}$  above sea-level. For the lower altitudes, the number of ROS events declines for all temperature increases beyond  $\Delta T = 0^\circ \text{C}$ . However, at the higher elevations, we observe an initial increase in the number of ROS events, from 37 to 51 for  $\Delta T = +2^\circ \text{C}$  at  $2000 \text{ m}$  and from 32 to 47 for  $\Delta T = +4^\circ \text{C}$ . Beyond these levels of temperature, the events decline thereafter; they are seen to drop beneath their current-climate values when  $\Delta T > +4^\circ \text{C}$  for the  $2000 \text{ m}$  level and  $\Delta T > +8^\circ \text{C}$  for at  $2500 \text{ m}$ . This is because even in a warmer climate there will still be the constitution of a snowpack above  $2000 \text{ m}$  (Gobiet et al., 2014). Even if the snowpack may be characterized by less thickness and shorter persistence in the future, the warmer conditions also enable liquid precipitation to occur at increasingly higher elevations, which will ultimately fall on the snow. It is only when temperatures are far in excess of the baseline levels that the snowpack duration and thickness will be significantly reduced and, as a consequence, most of the rain would be seen to fall upon snow-free terrain.

When decreasing or increasing precipitation with respect to current climate, and simultaneously increasing temperature, similar patterns emerge to those illustrated in Fig. 4. For example, the number of ROS events at  $2000 \text{ m}$  elevation are less numerous for a drier climate (17) and more frequent in a wetter scenario (67), but the same initial increase in the number of events is apparent  $\Delta T$  of up to  $4^\circ \text{C}$ , rising to 24 events in the “dry” climate and 73 in the “wet” climate. On the other hand, the ROS frequency declines rapidly at the lower elevations



**Fig. 4.** Identification of all ROS events at 1000 m (4A: upper frame) and 2500 m (4B: lower frame) from 1960 to 2015 ( $P > 50$  mm/day). The blue dots mark the ROS episodes and the red crosses identify the periods of high discharge ( $Q > 50$  m<sup>3</sup>/s).

because of the rarer snow cover in a warmer, drier climate; the decline is less rapid for the moist climate.

**3. Conclusions**

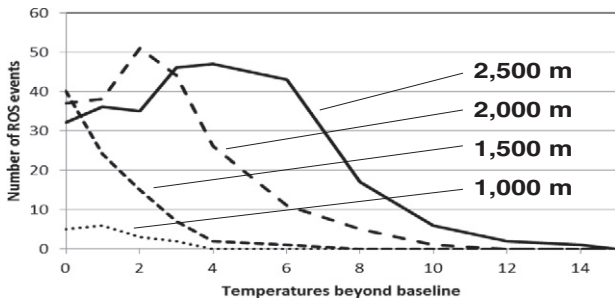
This study has shown that Alpine catchments such as the Sitter can be strongly affected by critical levels of runoff during events where liquid precipitation falls upon a pre-existing snowpack. The melting snow can, in the presence of heavy rainfall, provide significant amounts of water that rapidly converge towards mountain torrents and their tributaries, leading in some instances to severe floods. According to the Swiss flood database (WSL, 2016), the Sitter has exhibited over 20 local flood events since 1960. Four of these

(August 1978; May 1999; August 2005; and August 2007) are flagged by the database as major events and all except the 2007 flood are the result of ROS in the upper catchment zone.

The warming climate observed in this region has contributed directly to the increase in the number of ROS events. The warming climate observed in the 1960–2015 record has increased the number of ROS episodes in the Sitter River by about 40% at low elevations, and by >200% at the highest altitudes. While fortunately not all ROS events trigger catastrophic runoff, the risk of critical discharge obviously increases as a function of the number of such events.

The snow model suggests that even though warmer temperatures may serve to reduce the snowpack at low elevations, they also tend to increase the quantity of liquid precipitation which is likely to fall upon snow at higher altitudes, thereby increasing the risk of critical discharge. Our results show that the risk of such “critical flows” in the Sitter River linked to ROS events may rise with temperature increases of up to 4 or 5 °C, before this risk begins to decline beyond 5–6 °C above the current baseline. The ROS-related risks therefore get worse in a moderately warming climate before they improve in a strongly warming atmosphere, at least for the higher elevations.

Such conclusions – transposable to other Alpine catchments – can serve to guide future planning in terms of hazard mitigation measures and to improve the protection of populations located in potentially vulnerable zones. Recent flood events have shown quite clearly that damage to infrastructure and the potential for loss of life is high. Thus our projections as to a probable initial increase in the frequency of ROS-triggered floods as climate warms in the future should serve to stimulate early decision-making that aims at alleviating the more negative human and economic impacts of these events.



**Fig. 5.** Number of ROS events for temperature increases beyond the reference climate of the 1960–2015 time series, for the same levels of precipitation as the baseline climate, at 4 altitudinal levels.



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