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Rain-on-snow events in Switzerland: recent observations and projections for the 21st century

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ABSTRACT: We analyze the temporal and spatial patterns of rain-on-snow (*ROS*) events during the last 4 decades in Switzerland and project the future occurrence of *ROS* events based on atmospheric warming under the A1B greenhouse gas emissions scenario. The results indicate that *ROS* events occur mainly during winter months at low elevations, and during summer months at high elevations. The solid/liquid precipitation ratio and the duration of the snowpack explain the spatio-temporal characteristics of *ROS* events. Observations indicate a trend towards a slight reduction in *ROS* events during the study period (1972–2012) due to decreasing rainfall, and a reduction in snowpack duration due to warming temperatures. However, increased warming may increase the frequency of *ROS* events in future decades, especially at high elevations (>2000 m) where the snowpack will still be present during most of the year, but liquid precipitation will become more frequent.

KEY WORDS: Rain-on-snow events · Snowpack · Precipitation phase · Temperature · Alps · Switzerland

1. INTRODUCTION

Snowpack in mountainous regions is a valuable ecological, hydrological, and socioeconomic resource (Elsasser & Bürki, 2002, Barnett et al. 2005, Keller et al. 2005), but can also represent risks for population and infrastructures, in particular when these are exposed to snow avalanches (Schweizer et al. 2003). Mountain snowpack at mid-latitudes is a key source of water for rivers during snowmelt in the spring and summer months (Stewart 2009). However, rapid melting events occurring in specific atmospheric conditions can trigger floods in downstream basins, due to the aggregation of melt water from mountain tributaries (Sui & Koehler 2001).

Rain-on-snow (*ROS*) events, in which water from rainfall and snow melt accumulates dramatically in river channels, are particularly important phenomena. Such events can be a source of peak flows in mountain rivers, and can sometimes trigger floods and pose risks for population downstream (Floyd & Weiler 2008). Thus, most previous research of *ROS* events has taken a hydrological perspective (Singh et al. 1997, Sui & Koehler 2001, Floyd & Weiler 2008, Mazurkiewicz et al. 2008, Pradhanang et al. 2013, Rössler et al. 2014, Wever et al. 2014). Fortunately, most *ROS* events do not have catastrophic consequences, although they remain interesting phenomena in hydro-climatic and geographic terms. There has been very little focus on the climatic and spatio-temporal characteristics of *ROS* events, with the exception of the work by McCabe et al. (2007), Ye at al. (2008) and Rennert et al. (2009), who studied temporal and spatial trends of *ROS* events in the western

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United States, Eurasia, and circumpolar Arctic regions, respectively. However, the observed temperature increases over the past few decades and the projected global climate warming may increase the amount of precipitation that falls as rain (Gobiet et al. 2014, Stoffel et al. 2014) and affect the duration of the snowpack in mid-latitude mountainous regions (Beniston et al. 2003, Brown & Mote 2009). As a consequence, future changes in the spatio-temporal patterns of *ROS* events may have severe impacts on the hydrology of mountain areas, including the availability of water resources or the occurrence of floods.

In Switzerland, the snowpack is a major freshwater resource, and large areas of its mountains and uplands are covered by snow during winter months. Previous studies in Switzerland have shown that climate warming over recent decades has affected snowpack duration at low to middle elevations, but not yet at high elevations (Scherrer et al. 2004, Marty 2008, Beniston 2012, Morán-Tejeda et al. 2013). However, projected warming in future decades is expected to increase the altitude of the zero-degree isotherm during winter months, thereby reducing the depth and duration of the snowpack at increasingly higher elevations (Beniston 2012). This projected temperature increase would lead to changes in the precipitation phase ratio, with rain becoming more common and snow less common at increasingly higher elevations. This may increase the frequency of *ROS* events. Due to the steep hilly topography, floods are a recurrent phenomenon in Switzerland (Weingartner et al. 2003) as exemplified by episodes in May 1999, August 2005 (Beniston 2006), October 2011, and May 2015 on the Swiss plateau, in which rivers overflowed and affected major cities. The 1999, 2011, and 2015 events are classical examples of *ROS*-triggered floods that combined intense rainfall with elevated temperatures and above freezing temperatures at high elevations that lasted for several days (Schmocker-Fackel & Naef 2010). Although there is no long-term trend in the frequency of floods in Switzerland (Schmocker-Fackel & Naef, 2010), a warmer climate accompanied by increasing ROS events could lead to more frequent flooding.

In this study, we analyze the spatial and temporal patterns of variability in *ROS* events in Switzerland in relation to the changes in snowpack and climatic variables that have occurred during recent decades. We also project the occurrence and magnitude of future *ROS* events based on changes in temperature derived from regional climate models (RCMs) in future decades. These results serve as a starting point for further evaluation of the hydrologic impact of *ROS* events under conditions of climate change (CC) in mountainous regions where sustained snowpack will continue to exist.

2. DATA AND METHODS

2.1. Climatic data

Climatic data was provided by MeteoSwiss (www.meteoschweiz.ch) and included daily precipitation (mm), temperature (°C), and snow height (cm) series from 42 sites in Switzerland from 1972 to 2012. These sites range in elevation from 316 m a.s.l. (Basel) to 2690 m a.s.l. (Weissfluhjoch). Data from MeteoSwiss was carefully checked for errors and inhomogeneities, and there were missing values in some series. Thus, from the 42 original series that contained snow depth data, we used 25 series after quality control (Table 1). The included series had fewer than 5% of values missing during the study period. Data gap filling was performed by linear regression using the best correlated series (reference series) and

Table 1. Names, locations, and elevations of the 25 meteorological stations that provided data for the study of recent and projected rain-on-snow (*ROS*) events in Switzerland

ID	Name	Longitude (E)	Latitude (N)	Elevation (m a.s.l.)
s75	Basel	7.58°	47.54°	316
s51	Neuchâtel	6.95°	47°	485
s78	Bern	7.46°	46.99°	553
s27	Chur	9.53°	46.87°	556
s71	Zürich	8.57°	47.38°	556
s11	Meiringen	8.18°	46.73°	595
s7	Ebnat-Kappel	9.11°	47.27°	623
s14	Fribourg / Posieux	7.11°	46.77°	634
s17	Langnau	7.81°	46.94°	775
s56	St Gallen	9.4°	47.43°	779
s9	Einsiedeln	8.75°	47.13°	910
s8	Elm	9.18°	46.92°	965
s13	Château-d'Oex	7.14°	46.48°	985
s65	La Chaux-de-Fonds	6.8°	47.09°	1018
s28	Poschiavo / Robbia	10.06°	46.35°	1078
s30	Scuol	10.28°	46.79°	1298
s63	Adelboden	7.56°	46.49°	1320
s25	Sta. Maria, Val Müstair	10.42°	46.6°	1390
s10	Andermatt	8.59°	46.63°	1442
s19	Grächen	7.84°	46.2°	1550
s26	Davos	9.84°	46.81°	1590
s1	Arosa	9.67°	46.78°	1840
s91	Grimsel Hospiz	8.33°	46.57°	1980
s35	Säntis	9.34°	47.25°	2502
s73	Weissfluhjoch	9.81°	46.83°	2690

the candidate series (series with gaps), with a Pearson's R threshold of ≥0.7. If the candidate and reference series contained gaps within the same records, then the next best-correlated reference series was selected. When Pearson's R between the candidate and the reference series was <0.7, missing values were not corrected.

2.2. Snowpack and *ROS* events

ROS events are episodes in which rain falls onto a consolidated snowpack. McCabe et al. (2007) defined a *ROS* event as a 'day when precipitation occurred and snow depth decreased'. Such a criterion is somewhat ambiguous because this would include days that record both snowfalls and snowpack reduction due to melting or sublimation; in addition, a rain event on a tiny snowpack (e.g. 1 cm depth) can be negligible. For defining *ROS*, precipitation partitioning or the 'precipitation phase' (amount of water in liquid and solid phases) must be considered. To this end, we used a simple approach to estimate precipitation partitioning (Feiccabrino et al. 2012, Marks et al. 2013), based on a linear transition from snow to rain depending on mean temperature. Thus, all precipitation was classified as snow if the mean temperature was <–1°C and as rain if the mean temperature was >+3°C. We defined a linear transition from snow to rain for temperatures of –1 to +3°C using the relation:

$$r = -0.25 \times T + 0.75,\ T = [-1, 3] \quad (1)$$

where T is the mean temperature (°C) on a given day and r is the snow:rain ratio (precipitation phase; S:R) of that day. Values range between 1 (100% snow) and 0 (100% rain).

Based on the above considerations, and after computation of the snow:rain ratio for each precipitation event, we defined a *ROS* event as a day with snow depth >5 cm and a rainfall event >5 mm that resulted in snowpack reduction the following day. The magnitude of a *ROS* event was determined from the above ratio applied to the amount of rainfall of that day. We then calculated the number of *ROS* events, $S{:}R$, *ROS* magnitude (ROS_m), snow depth (*SD*), and snowpack duration (*SpD*) for every month and year from 1972 to 2012. Table 2 summarizes all indicies and their definitions.

2.3. Trend analysis

The Mann-Kendall (MK) test was used to determine temporal trends in *ROS* events and climate variables. This non-parametric test has been broadly used in climatologic studies for detecting trends because it prevents outliers or non-normal distributions from affecting the probability of rejecting the null hypothesis (no trend). This test provides 2 parameters that are useful in characterizing trends: (1) the MK coefficient (tau), which indicates the sign

Table 2. Climatic indices used for statistical analysis and modeling of rain-on-snow (*ROS*) events in Switzerland

Index	Abbreviation	Definition	Unit
Rain-on-snow event	*ROS*	Day with snow depth >5 cm and a precipitation event >5 mm that resulted in snowpack reduction the following day	–
Precipitation phase	$S{:}R$	Ratio of snow:rain resulting from multiplying the result of Eq. (1) by the precipitation of a given day	–
Rain-on-snow magnitude	ROS_m	Quantity of rain during a *ROS* event	mm
Snow depth	*SD*	Depth of the snowpack for a given day	cm
Snowpack duration	*SpD*	Number of days with snowpack >5 cm	No. of d
Beginning of snow season	*BS*	First day of the season after 10 consecutive days with snow depth >5 cm	Day of the year from October 1
End of snow season	*ES*	Last day of the last spell of the season with 10 consecutive days with snow depth >5 cm	Day of the year from October 1
Degree-days	*DD*	Cumulative sum of temperature degrees of above-zero days from October 1	°C
Millimeter-days of freezing days	MD_f	Cumulative sum of precipitation millimeters of days with negative temperature from October 1	mm
Millimeter-days of above-zero days	MD_w	Cumulative sum of precipitation millimeters of days with positive temperature from October 1	mm

and strength of the trend; and (2) the statistical significance level for rejecting the null hypothesis of no trend, which in this study was set to 0.05 (i.e. the 95% confidence level). Prior to applying the trend test we applied a trend-free prewhitening procedure (Yue et al. 2002) to remove autocorrelation (if present). This entire procedure was performed using the R 'zyp' package (Bronaugh & Werner 2013).

2.4. Modelling the duration of snowpack and the occurrence of *ROS*

Given the regional nature of the work, we aimed at projecting a general picture of plausible future occurrence of *ROS* in Switzerland under warming conditions, based on a simple approach that would enable extrapolation of our results to other similar territories. This regional conception, together with the available data, prevented us from considering the use of more advanced and complicated methods for simulating future *ROS* occurrence, including physical land surface or energy balance models that are time consuming and very dependent on the specific characteristics of the sample site.

Thus our purpose was to create a regional statistical model that would enable estimation of *SpD* and the occurrence of *ROS* events under conditions of CC, based on the same independent variables for the whole Swiss mountain territory. For this procedure, we selected stations located above 900 m, which had a sustained snowpack throughout the winter. Lower-elevation stations such as Basel, Zürich, and Neuchâtel have snowfalls and snowpack during winter, but snowy days and snow cover are intermittent. The beginning and end of the snow season (*BS* and *ES*) are defined as the first and last days of the season (counting days of the year from October 1) with snow depth >5 cm, provided that at least the 10 previous days had a snowpack >5 cm and there was uninterrupted snowpack between those dates. The *BS* and *ES* for each location and each year from 1972 to 2012 were considered as dependent variables for 2 models. The predictors (independent variables) included in the models were 'cumulative degree-days of above-zero days' (*DD*), 'cumulative millimeter-days of freezing days' (MD_f), and 'cumulative millimeter-days of above-zero days' (MD_w) for different dates towards the end of autumn and spring (Table 2). These variables were constructed based on the combination of 2 concepts: the degree-day method for estimating snow accumulation and melt (Rango & Martinec 1995, Hock 2003, Braithwaite 2008), which is based on the assumption that total daily snowmelt depends on the temperature difference between the mean daily temperature and a baseline temperature (generally 0°C); and the growing or cumulative degree-days used in agronomy, as a measure of heat accumulation up to a certain date (Rohrer et al. 2013). Analogously, we considered these cumulative indices (temperature and precipitation of freezing and non-freezing days since a certain date) as representative of the accumulation and ablation of snowpack, and therefore used them as predictors in our statistical model.

A problem associated with the use of the same covariates for the whole territory, in terms of statistical modeling, is that the different meteorological stations have unique geographical locations, elevations, and orientations. This can imply a large amount of variance, commonly known as random effects, which cannot be accounted for by a simple linear model. An example of this is that the baseline of the predicted variables *BS* and *ES* will be different for each station. For example, the mean *ES* day at Davos is day of the year 208 (April 25) whereas *ES* at Château-d'Oex is day of the year 170 (March 18). To apply a general model for all stations, considering the variance accounted for by random effects, we generated a linear mixed-effects model (generalized least squares; Winter, 2013). This approach accounts for the variance explained by random effects, such as those from the peculiarities of each sample point. In our models the fixed effects were the independent variables (*DD*, MD_f and MD_w, see Table 2), and the random effect is given by the ID of each station. Thus, the models had the form:

$$BS(ES) \sim DD + MD_f + MD_w + (1|ID) + \varepsilon \qquad (2)$$

where *BS* and *ES* are the dependent variables, *DD*, MD_f and MD_w the independent variables, the term in parentheses indicates the random effect accounted for by the station ID, and ε is the error term, or residual variance (other random effects) that we cannot account for.

After confirming that *BS* and *ES* were properly modeled as a function of climatic variables, we performed future projections by considering temperature changes for different future time windows. These were derived from runs of the RCMs from the ENSEMBLES project (Van der Linden & Mitchell, 2009). ENSEMBLES originally consisted of 22 RCM simulations until 2050 (15 until 2100) at resolutions of 25 and 50 km, and boundary conditions from 8 different Global Climate Models under the A1B greenhouse gas scenario. Gobiet et al. (2014) reviewed possible changes in the Alps using ENSEMBLES runs. We selected the 15 RCMs that had simulations until 2100 and considered the time windows of 1972–2009 (control), 2010–2039, 2040–2069, and 2070–2099. We calculated differences (deltas) between the mean (centered) monthly temperature of each future time window and the mean monthly temperature of the control period for each RCM. To summarize the changes projected by each RCM with consideration of variability, we computed the intermodel mean, 25th percentile (p25), and 75th percentile (p75) of the deltas for each time window.

The computed monthly deltas were then applied to the temperature data to generate 9 CC temperature scenarios (Table 3). These CC temperature sets were then used in Eqs. (1) & (2) to compute snowpack duration and the occurrence of *ROS* under conditions of CC. We decided to not explore future changes in precipitation in our projections of future *ROS* occurrence. This may seem contradictory to our aims, as *ROS* are basically rainfall events and any change in rainfall patterns (especially in the frequency of rainfall events) would lead to changes in *ROS* occurrence. However an exploration of the changes in precipitation amounts for future time-windows driven by the ENSEMBLES RCMs showed that the signal of change was inconsistent season-wise and amongst RCMs, and comparable to the range of estimations given by Switzerland's official CC scenarios (Bey et al. 2011). This is confirmed by the most recent evaluation of precipitation projections for Switzerland (Fischer et al. 2015), also based on the ENSEMBLES project. According to this, only summer precipitation shows a consistent change by the end of the present century, with a decrease in the frequency of wet days and in turn, in the mean precipitation amounts. However, this decrease will not be significant in high elevation regions. The rest of the seasons, either do not show a significant and consistent change, or show changes whose signals and magnitudes vary among the Swiss regions. Considering all possible ranges of future changes in precipitation, and the aforementioned differences by season and region, would have introduced large amounts of uncertainty into our results. In order to simplify the interpretation of results only the future occurrence of *ROS* events as a result of changing temperatures was evaluated.

3. RESULTS

3.1. Temporal and spatial patterns in snow and *ROS* events from observations (1972–2012)

Figs. 1 & 2 show the seasonal patterns of *SD*, *SpD*, *S*:*R*, and *ROS* events as a function of elevation, and the trends of each indicator during the observation period 1972 to 2012. *SD* and *SpD* had similar seasonal patterns, indicating the presence of thin snowpack from November to March on mountain surfaces <1500 m a.s.l., and a continuous consolidated snowpack from October to July at elevations >2000 m a.s.l. They also had similar temporal trends, with decreases during spring months for elevations of 1000 to 1400 m a.s.l., and decreases during May to July for elevations of 1800 to 2200 m a.s.l. In the case of *SD*, however, the trends were not statistically significant. *S*:*R* showed the same month-elevation patterns as *SD* and *SpD*. However, we must emphasize that the *SD* and *SpD* values are derived from direct observations, whereas the *S*:*R* values were calculated using Eq. (1) as a linear function of temperature. Nevertheless, the similarity in the patterns in *S*:*R*, *SD*, and *SpD* indicates that our method is appropriate for estimation of *S*:*R*. Moreover, the *S*:*R* values had a significant negative trend from mid-

Table 3. Monthly changes in temperature (°C) over Switzerland between the centered means of 3 time periods (2010–2039, 2040–2069, and 2070–2099) based on the A1B emissions scenario, relative to the control time period (1972–2009). The 25th percentile (p25), 75th percentile (p75), and mean are shown for each scenario

Scenario	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2025												
p25	0.49	0.83	0.35	0.55	0.63	0.69	1.27	0.89	0.70	0.73	0.72	0.40
Mean	0.95	1.09	0.83	0.78	0.95	0.91	1.33	1.28	1.11	0.90	0.90	0.95
p75	1.25	1.24	1.20	1.03	1.26	1.17	1.61	1.62	1.44	1.12	1.04	1.30
2055												
p25	1.90	2.23	1.33	1.29	1.84	1.84	2.23	2.50	2.01	1.72	1.85	2.04
Mean	2.39	2.42	1.89	1.81	2.19	2.42	2.66	2.95	2.50	2.20	2.24	2.29
p75	3.00	2.56	2.28	2.29	2.31	2.82	2.79	2.99	2.79	2.41	2.58	2.73
2085												
p25	3.12	2.84	2.02	2.13	2.79	3.51	3.97	3.76	2.70	2.60	3.39	3.44
Mean	3.44	3.37	2.86	2.63	3.39	3.74	4.23	4.36	3.78	3.28	3.65	3.72
p75	3.94	3.64	3.45	3.09	3.81	4.03	4.38	4.62	4.48	4.08	4.18	4.33

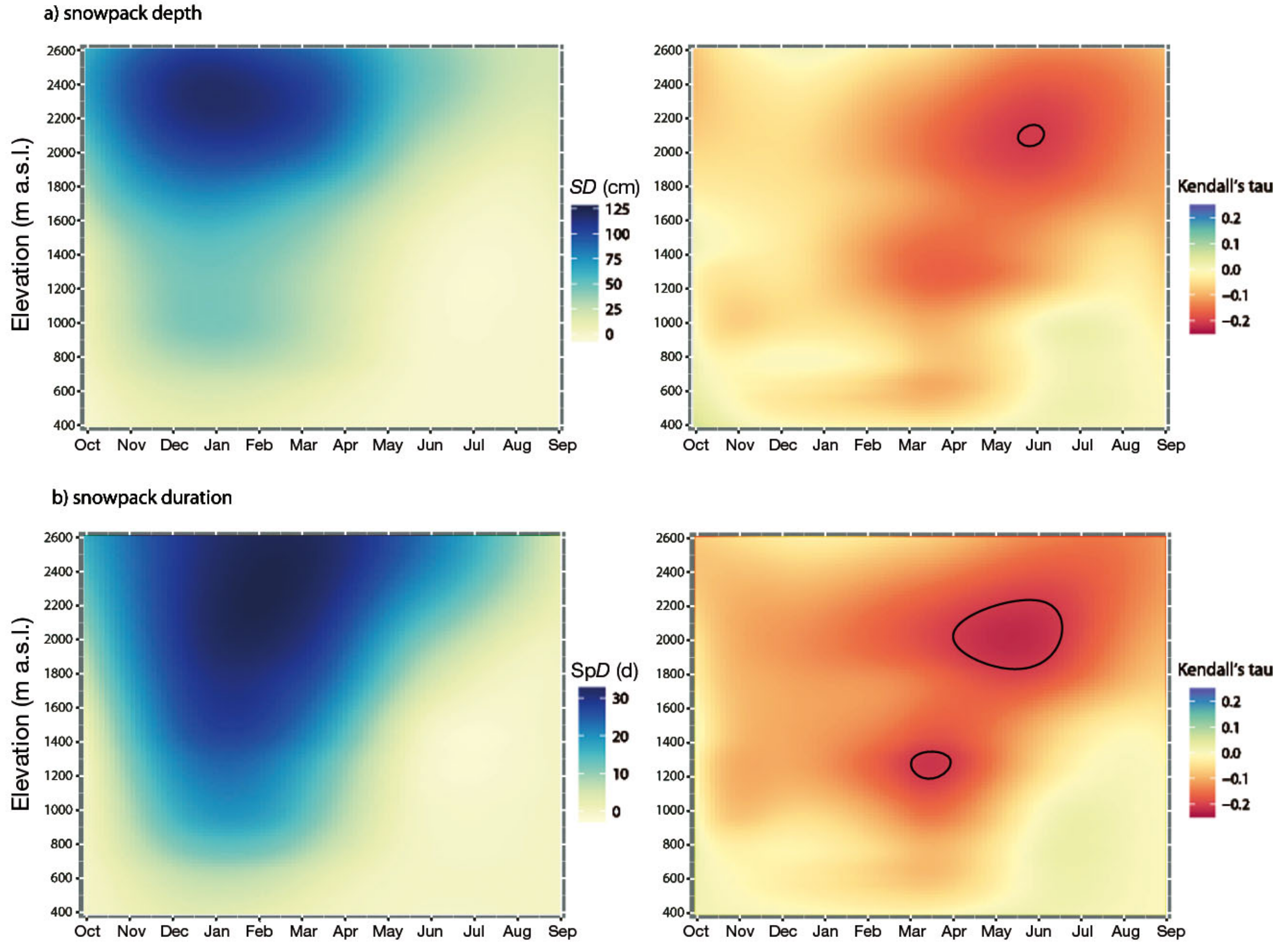

Fig. 1. Seasonal patterns of long-term (1972–2012) (a) snow depth (*SD*) and (b) snowpack duration (*SpD*) (left panels) and their respective trends (Mann-Kendall's tau values) (right panels) as a function of elevation. Smoothed colored surfaces result from application of a local polynomial interpolation (LOESS) and, in the right-hand panels, black contour lines indicate significant trends at the 95% confidence level

February to mid-July along an elevation gradient; this indicates that increasing temperatures are the main factor responsible for the negative trends in *SD* and *SpD* during spring and summer. Finally, *ROS* events had a bi-modal spatio-temporal pattern. At altitudes of 700 to 1100 m a.s.l., *ROS* events occurred mostly during the winter months and March, with 2 events mo^{-1} in this period each year. At altitudes of 1200 to 1800 m a.s.l., 1 to 1.5 events mo^{-1} occurred between December and March each year. By contrast,at high-elevations (>2000 m a.s.l.), *ROS* events tended to occur from April to July, with nearly 3 events mo^{-1} during this period in each year.

This pattern can be explained by the behavior of the snowpack and precipitation phase. At low elevations, the snowpack extended from December to March and many precipitation events occurred during above-freezing days, and these resulted in *ROS* events. At middle elevations, most precipitation events during winter occurred during below-freezing days, so the number of *ROS* events was lower. At high-elevations, the number of *ROS* events dropped to zero during winter months, because all precipitation fell as snow (Fig. 2a). During spring and summer, by contrast, snowpack remained at high altitudes, and the *S*:*R* ratio dropped, thus favoring the occurrence of *ROS* events. Finally, there was a predominance of negative Kendall values in *ROS* events, although there was no significant general trend for the period under investigation.

Fig. 3 shows the MK coefficients for yearly *ROS* events and the hydro-climatic explanatory variables at the study sites by elevation. Precipitation generally had negative coefficients, but only 5 stations had significant negative trends, and there was no apparent influence of elevation on the sign of the coefficients. Mean temperature had a general and significant increase at most stations, regardless of eleva-

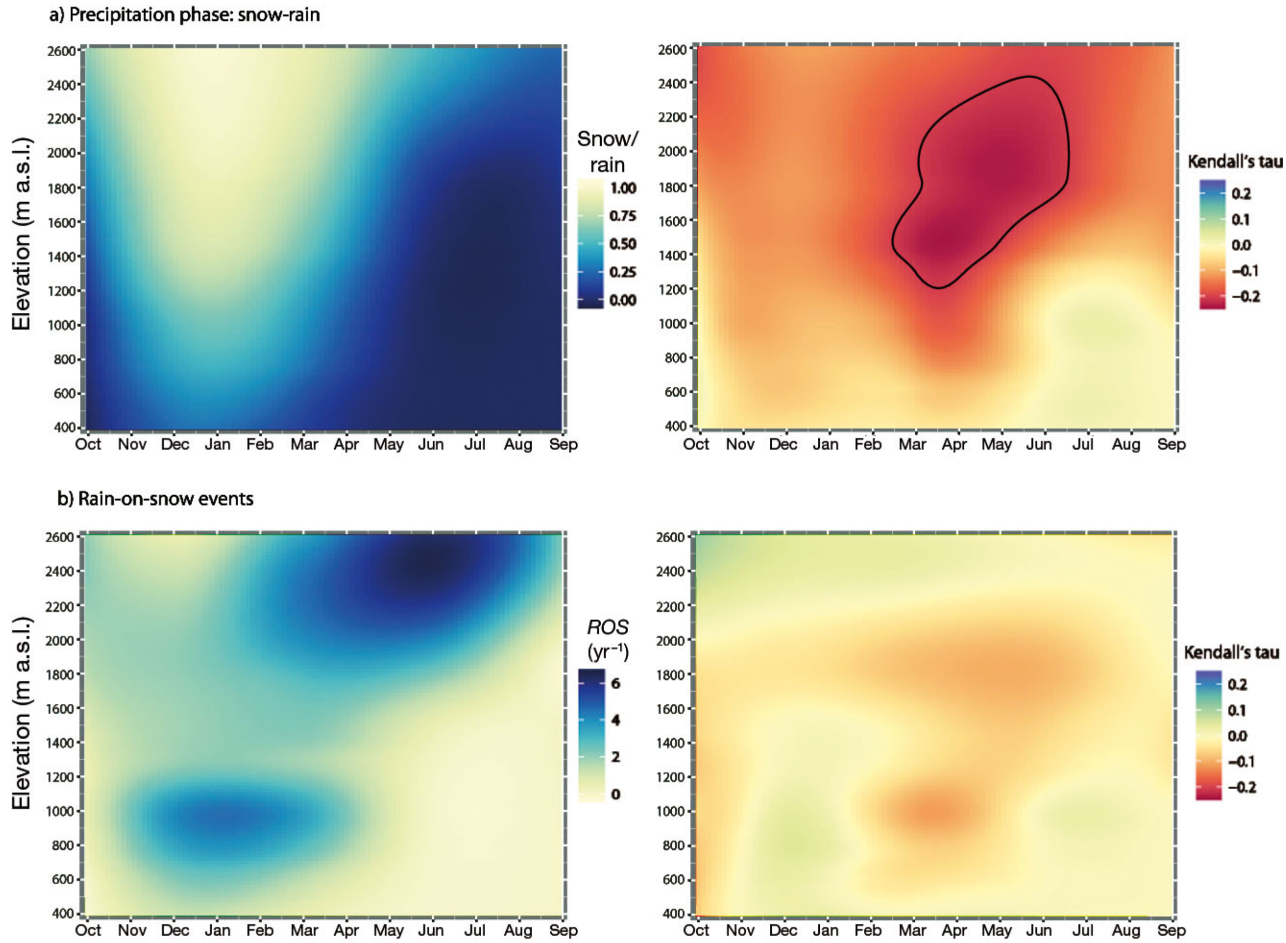

Fig. 2. Seasonal patterns of (a) the long-term (1972–2012) precipitation phase, i.e. the snow:rain ratio (*S*:*R*) calculated from Eq. (1), and (b) annual occurrence of rain-on-snow (*ROS*) events (left panels) and their respective trends (Mann-Kendall's tau values) (right panels) as a function of elevation. Smoothed colored surfaces result from application of a local polynomial interpolation (LOESS) and, in the right-hand panels, black contour line indicates significant trend at the 95% confidence level

tion. *SD* and *SPd* generally had negative trends during the study period, and these were greater in magnitude at higher elevations. Finally *ROS* and ROS_m tended to have negative coefficients, but there were only significant trends at 4 stations for *ROS* and 5 stations for ROS_m. Elevation appeared to play no role in the sign and magnitude of the trends in *ROS* and ROS_m except at the highest sites where positive coefficients occur at 2 of the 3 stations that were at elevations >1900 m a.s.l.. The correlations between the MK coefficients for precipitation and *ROS* events (R^2 = 0.53) and ROS_m (R^2 = 0.63) are particularly notable. This indicates that the observed decrease in *ROS* events was related to the decrease in rainfall during the study period.

Fig. 4 shows the mean yearly number of *ROS* events and the mean ROS_m with their coefficients of variation as a function of hypsometry. This figure shows the percentage of Switzerland that is likely to experience *ROS* events under the current climate. Nearly 20% of Switzerland is >2000 m a.s.l., where an average of 20 *ROS* events occur per year (yearly variation ~40%). The magnitude of such events is about 100 mm yr^{-1}. The altitudinal distribution of annual *ROS* events is similar to that in Fig. 2, whereas the ROS_m shows an almost exponential increase up to 2500 m a.s.l. and a slight decrease at >2500 m a.s.l.. Although there is no data for elevations at >2700 m a.s.l., it is likely that the number and magnitude of *ROS* events are lower at these elevations due to the persistence of the zero-degree isotherm (and thus the prevalence of snowfall over rainfall) throughout the year. Fig. 4 also shows that the yearly variation in *ROS* events and overall ROS_m is inversely proportional to the number and magnitude of *ROS* events; in other words, stations at the lowest (highest) elevations had the greatest (smallest) variability. Variability peaked at elevations between 400

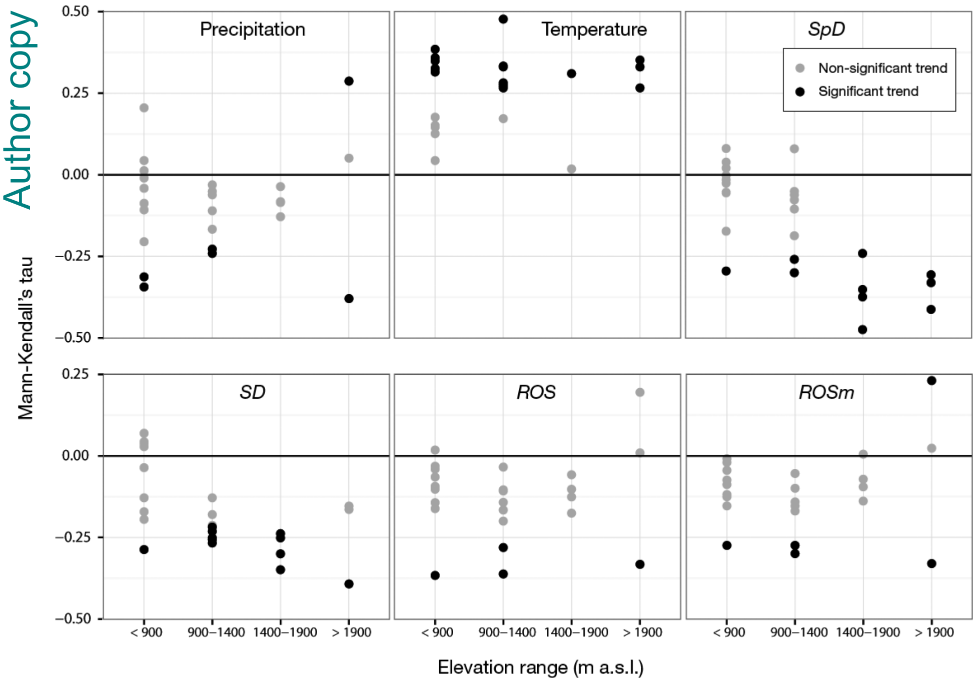

Fig. 3. Mann-Kendall tau values for precipitation, temperature, snowpack duration (*SpD*) snow depth (*SD*), rain-on-snow (*ROS*) events and rain-on-snow magnitude (ROS_m) at Swiss weather stations (Table 1) grouped according to elevation

and 600 m a.s.l. and between 1200 and 1600 m a.s.l. The peak at 400 to 600 m a.s.l. can be explained by the lack of a sustained snowpack during winter; the peak at 1200 to 1600 m a.s.l. is due to the behavior of the precipitation phase, because S:R was close to 1 from December to February and close to 0 during the rest of the year (Fig. 2).

The snowpack <~900 m a.s.l. was somewhat sporadic (Fig. 1). Since a continuous variable is needed for modeling purposes we focus our analysis on locations above 900 m a.s.l. in the following section.

3.2. Future snowpack and *ROS* events

We applied the model of Eq. (2) to predict *BS* and *ES* as a function of climatic variables. Independent variables (fixed effects) were included step-wise, and models with 1, 2, and 3 fixed effects were compared by ANOVA. The fitted models were:

$$BS = a^{*} - b^{*}\ MDf_{\mathrm{dec}} + 0.04DD_{\mathrm{nov}} \quad (3)$$

$$ES = a^{*} + b^{*}\ DD_{\mathrm{may}} + 0.015MDf_{\mathrm{may}} \quad (4)$$

where * indicates that the coefficient varies according to the station considered. Thus the main predictors for *BS* are the accumulated precipitation during freezing days as of December 31 (MDf_{Dec}) and the accumulated degrees during above-zero days as of November 30 (DD_{Nov}). The main predictors for *ES* are the accumulated degrees during above-zero days (DD_{May}) and accumulated precipitation during freezing days (MDf_{May}) as of May 30. Both models were set up for a training period (1972–2001) and were validated for an independent test period (2002–2011). The evaluation of the performance of models for the training set and test set was based on 4 statistics computed to compare observed and estimated values: the correlation (Kendall's correlation) and Nash-Sutcliffe efficiency (NSE), which both evaluate the fit between observations and simulations (the closer to 1, the best fit); the root mean square error (RMSE) which represents the standard deviation of the residuals, and the percent bias (PBias), which informs of systematic over- or underestimations of simulations with respect to observations. Table 4 shows the validation statistics. In general we observe that the statistics of agreement between observations and model's estimates are fairly good, although the model for *ES* is better than that for *BS*. It is remarkable that the values for the test period do not differ largely from the values for the training period, indicating that the models perform similarly well for an independent data sample. We thus consider the fitted models appropriate for the purpose of this study.

Fig. 5 shows the simulated duration of the snowpack by representing *BS* and *ES* under current conditions and under future CC temperature scenarios. Based on the aforementioned model fits, we simulated *BS* and *ES* under different warming scenarios given by the suite of ENSEMBLES RCMs. The amplitude of the shaded areas indicates that *ES* is much more sensitive to climate warming than *BS*. On average, considering the multi-model mean, *ES* would occur 8 d earlier (standard deviation: ±3) than present by 2025, 21 d earlier (±8) by 2055 and 34 d earlier (±13) by 2085. According to the multi-model mean, *BS* would be delayed by 4 d (±1.8), 7 d (±2.3), and 10 d (±2.4) by 2025, 2055, and 2085, respectively.

Considering the changes in *SpD* and S:R (Eq. 1) under warming conditions, we projected future changes in *ROS* events for our different CC tempera-

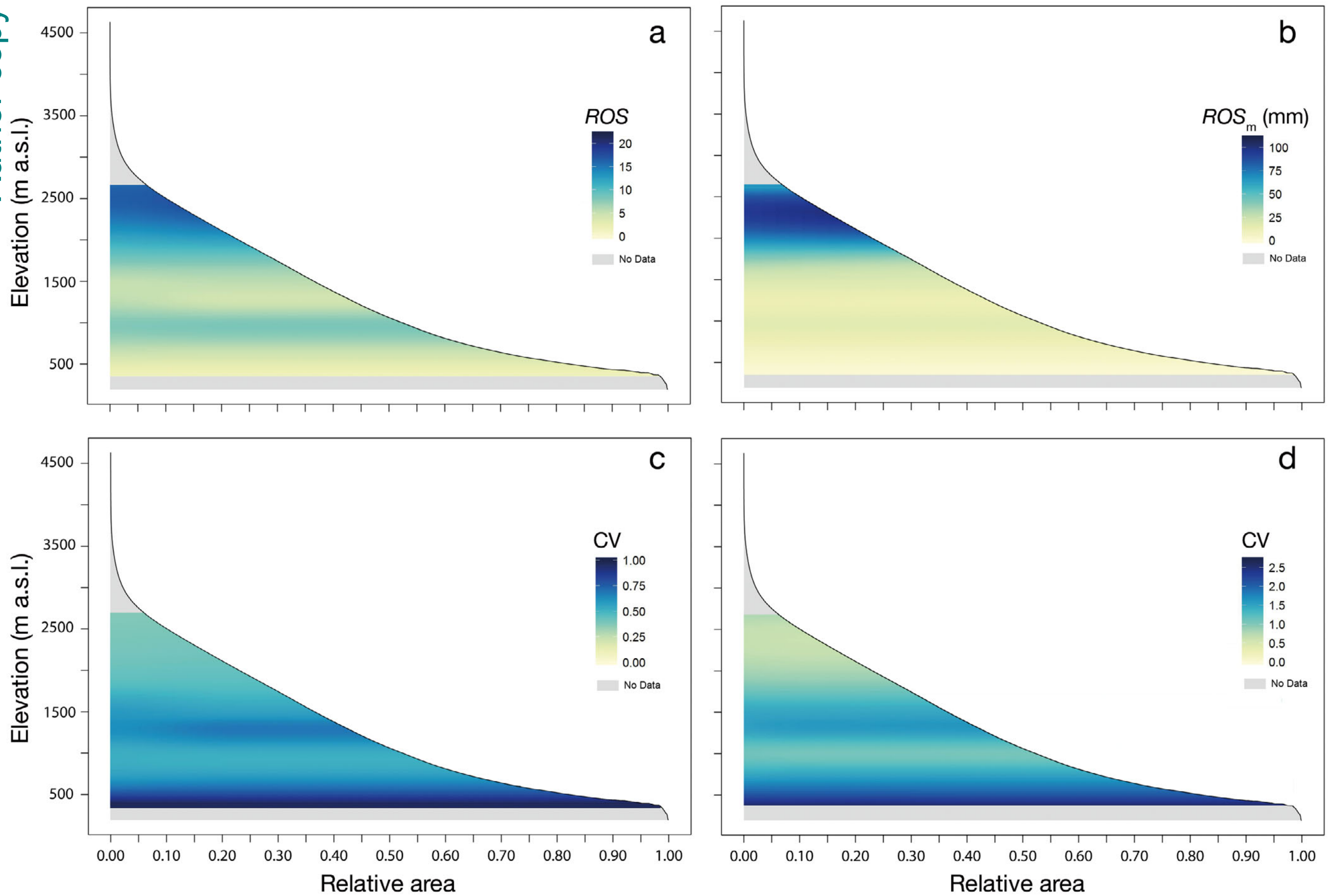

Fig. 4. Hypsometry of Switzerland with the corresponding (a) mean annual occurrence of rain-on-snow (*ROS*) events and (b) the mean annual rain-on-snow magnitude (ROS_m) (top panels) and their coefficients of variation (bottom panels) during the study period (1972–2012)

Table 4. Validation statistics for models used to predict the beginning (*BS*) and end of the snow season (*ES*) at selected Swiss weather stations (Table 1), based on comparison with observations during the training period 1972–2001 and test period 2002–2011. Cor: Kendall's correlation; NSE: Nash-Sutcliff efficiency coefficient; RMSE: root mean square error; PBias: percent bias

	BS model		*ES* model	
	Training	Test	Training	Test
Cor	0.53	0.42	0.73	0.69
NSE	0.51	0.46	0.84	0.83
RMSE	18.4	18.1	19.3	23.3
PBias	−2.02	−10.6	0.01	2.2

ture scenarios. Fig. 6 shows changes in the number of annual *ROS* events for each station at >900 m a.s.l., and indicates that the response at a station depends on elevation. Thus, for stations at <2000 m a.s.l., the models predict fewer *ROS* events by 2025 and 2055, and values similar to those under current conditions by 2085. By contrast, for stations above 2000 m a.s.l., the models indicate a clear and sharp increase in the annual number of *ROS* events, especially under conditions of enhanced atmospheric warming. This increase does not occur under the scenario of least severe warming (p25 in 2025), and the models even project a decrease in the number of *ROS* events under this scenario.

For a better understanding of this differential behavior as a function of elevation, we further examined the monthly distribution of projected changes in *ROS* events (Fig. 7). In general, an increase in the number of *ROS* events is projected during winter months and a decrease during summer months, and these responses are stronger with more severe warming. However, this pattern is elevation-dependent, in that the increase of *ROS* events during winter has a longer time span (November to April) at high elevations, but is shorter at low elevations.

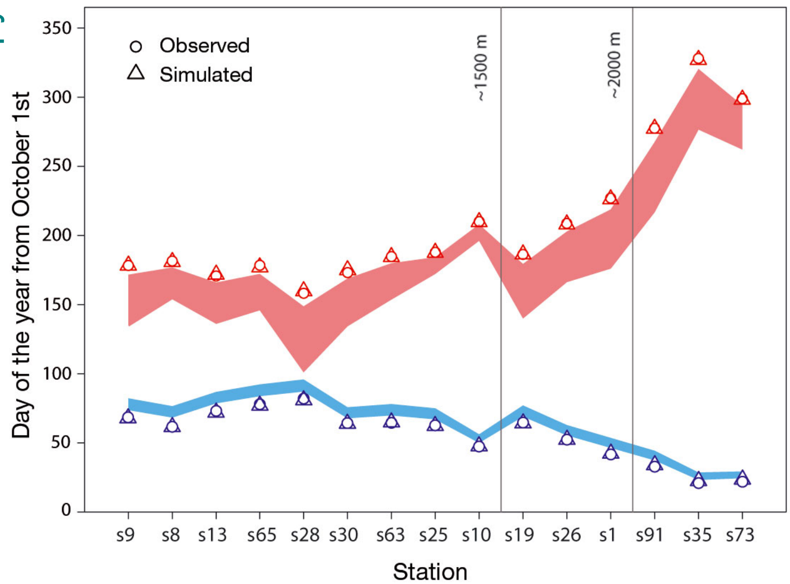

Fig. 5. Beginning (blue) and end (red) of the snow season at 15 Swiss meteorological stations above 900 m a.s.l. (ordered from lowest to highest elevation; see Table 1). Symbols show observed and simulated current values and shaded areas show the range of simulated future values between the least severe (25th percentile) scenario in the year 2025 and the most severe (75th percentile) scenario in the year 2085 (see Table 3)

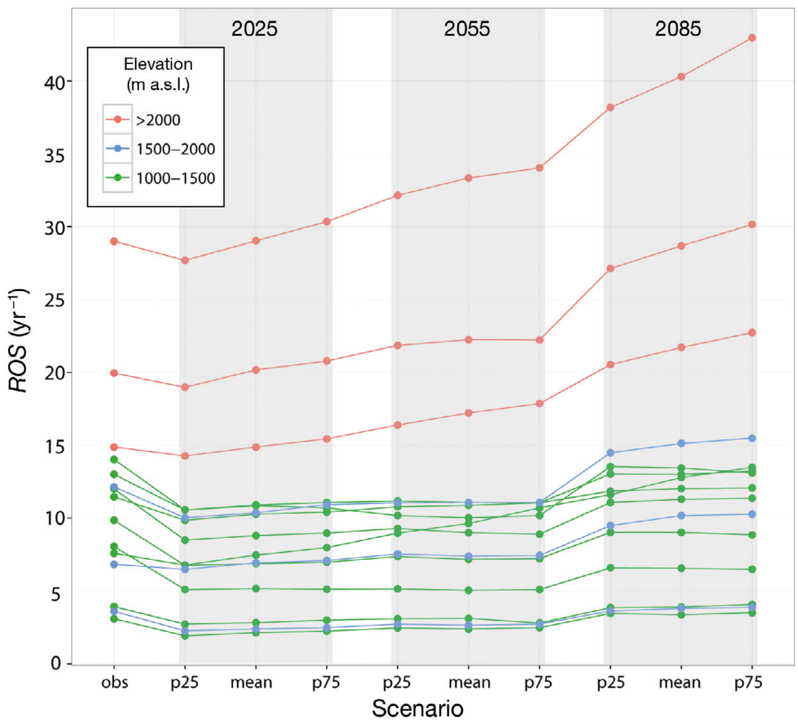

Fig. 6. Observed rain-on-snow (*ROS*) events from 1972 to 2009 and simulated *ROS* events for climate change scenarios (A1B emissions scenario projected to 2025, 2055 and 2085) for 15 Swiss meteorological stations above 900 m a.s.l. (see Table 1), grouped by elevation range, over different time horizons. 'p25' and 'p75' are 25th and 75th percentile simulated values, respectively

Fig. 8 shows the consequences of these changes. As a result of CC, there are more *ROS* events at high elevations, but fewer changes at low to middle elevations because of the reduced snowpack duration.

4. DISCUSSION AND CONCLUSIONS

ROS events are hydro-climatic phenomena that occur under specific meteorological and geographical conditions. We focused on the spatial and temporal patterns of *ROS* events and the meteorological variables that explain their occurrence. *ROS* events can be triggered by the co-occurrence of 3 basic conditions: a consolidated snowpack, a rainfall event, and warm air temperature. Air temperature is the main variable controlling the precipitation phase (i.e. the quantity of snow and rain during a precipitation event). The occurrence and seasonal distribution of *ROS* events are clearly affected by elevation. At 800 to 1200 m a.s.l., *ROS* events mostly occur during winter months, since at these altitudes both rain and snow can fall in winter, depending on the elevation of the zero-degree isotherm. However, the frequency of *ROS* events peaks during spring and summer at altitudes >2000 m a.s.l., where snowpack is more persistent and liquid precipitation events tend to exceed solid precipitation episodes. Based on the observed increase in temperature, it might be expected that ROS events have increased in recent decades. However, our observations indicated that *ROS* events have actually decreased in Switzerland, although most of the negative coefficients were not statistically significant. This is because of the decrease in rainfall and the shorter duration of the snowpack countered effects of temperature increases. Thus, the trends in *ROS* events observed by McCabe et al. (2007) in the western USA from 1949 to 2003, with decreasing frequency at low elevations and increasing frequency at high elevations, have not occurred in Switzerland. However, our projections anticipate these trends in Switzerland for future decades.

We considered the dependence of *ROS* events on the presence of snowpack, rain-

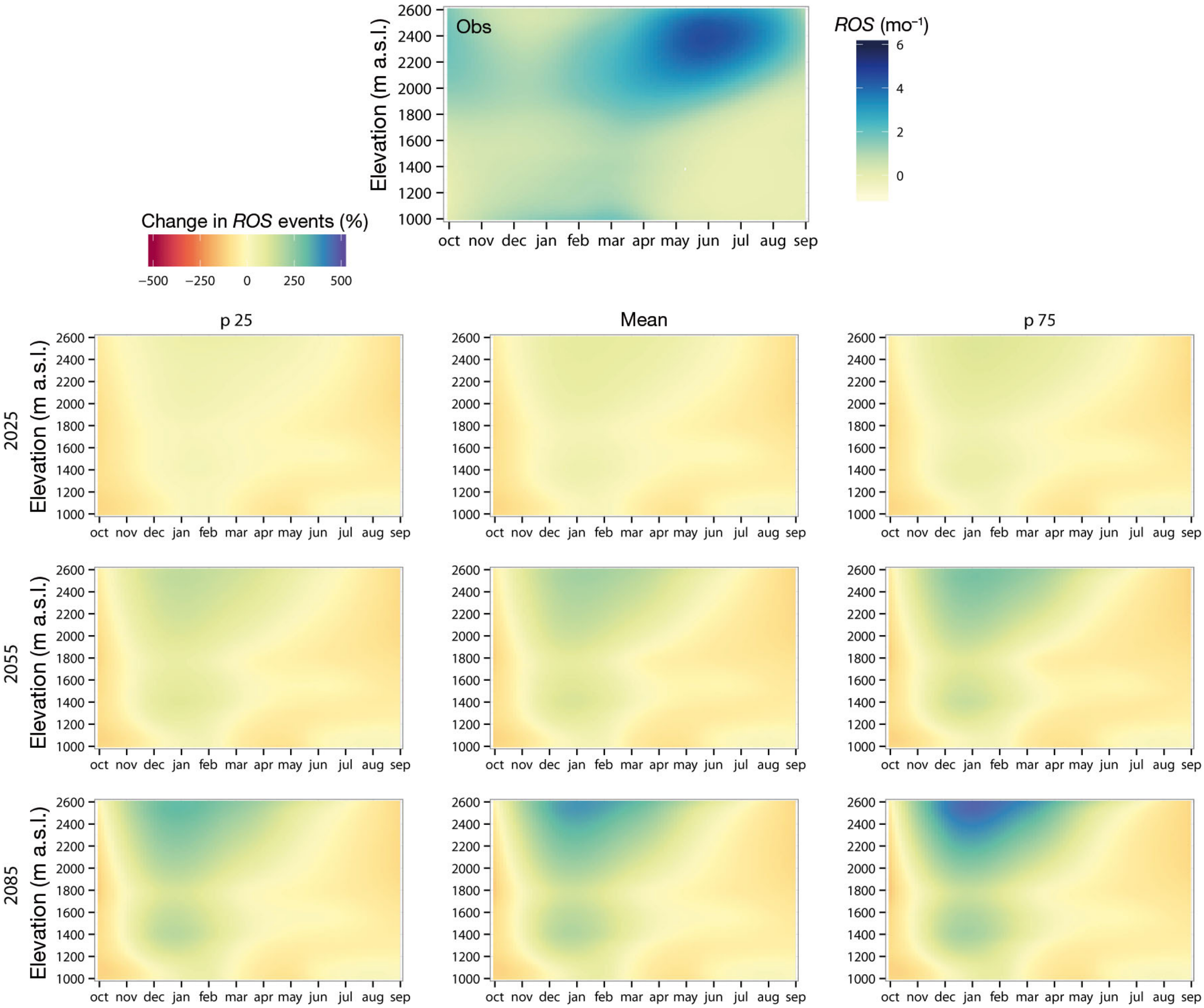

Fig. 7. Estimated changes in monthly occurrence of rain-on-snow (*ROS*) events for climate change scenarios (A1B emissions scenario projected to 2025, 2055 and 2085), relative to observations for the control time period (1972–2009; shown for reference in the top panel). Smoothed colored surfaces are from application of a local polynomial interpolation (LOESS). 'p25' and 'p75' are 25th and 75th percentile simulated values, respectively

fall, and temperature as a basis for a simple statistical approach to predict future spatio-temporal trends of *ROS* events. This approach combines the calculation of *S*:*R* with the use of a linear model to estimate *SpD*. We want to emphasize that the selection of this procedure, over the use of a more sophisticated physical simulation, was based on the regional scale of the work and on the fact that the 2 drivers of *ROS* frequency, i.e. *SpD* and *S*:*R*, have been proved to be strongly dependent on temperature. According to the projections, *SpD* will decrease under CC scenarios because of earlier melting of the snowpack and a related earlier *ES* due to increasing temperatures. This result agrees with the findings of Beniston et al. (2003), whose numerical simulations showed that *ES* is more sensitive to warming than *BS*. In this context, and considering no changes in precipitation, the future occurrence of *ROS* events will largely depend on the extent of temperature increase and the elevation of the site. Assuming a warming scenario predicted by the 25th multi-model percentile, *ROS* events will continue to decrease at all of our stations until 2025; the same trend will occur at all stations at <2000 m a.s.l. until 2055 according to all projections. By contrast, there is likely to be an increase of *ROS* events from 2055 to 2085 in locations >2000 m a.s.l..

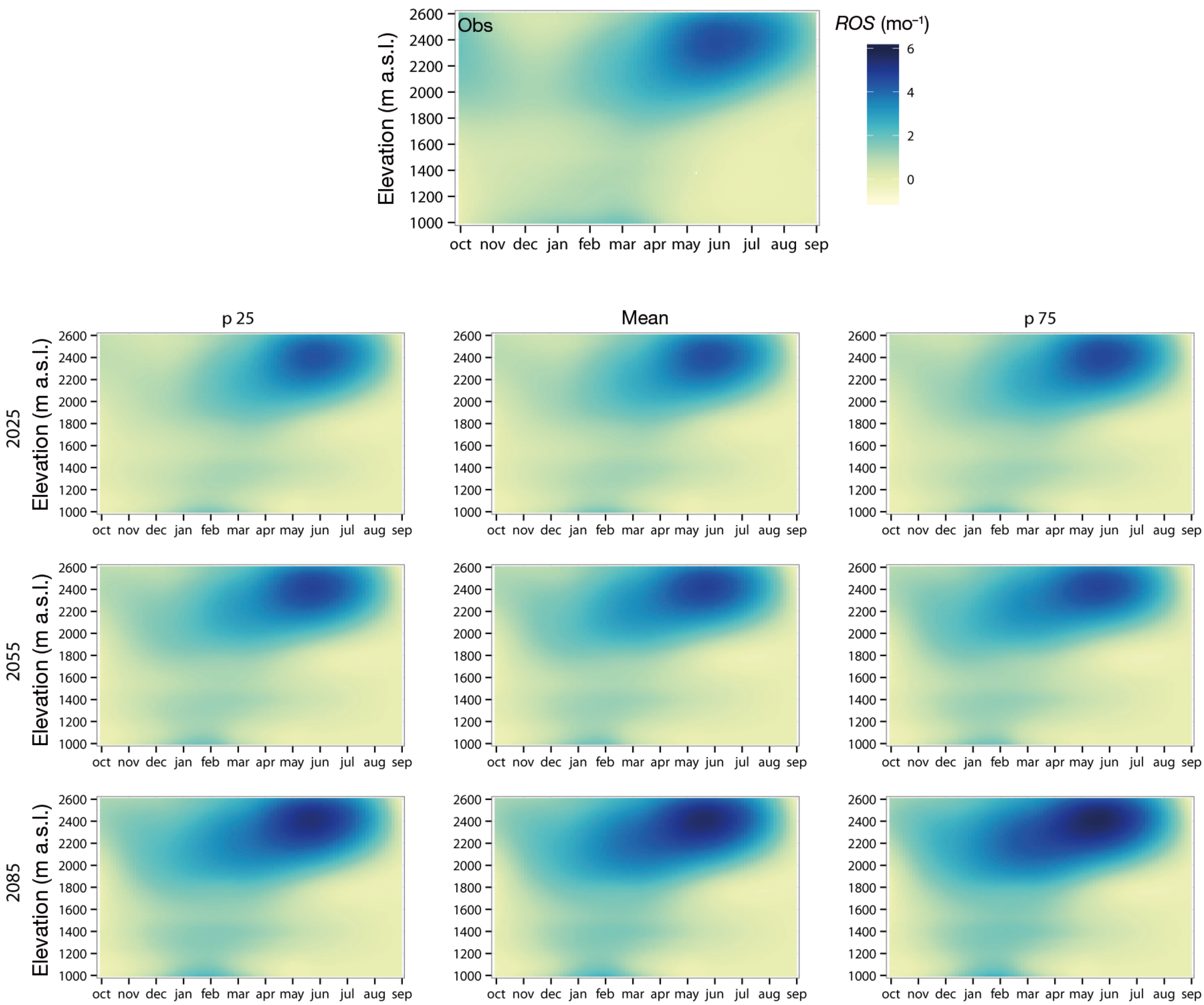

Fig. 8. Estimated monthly occurrence of rain-on-snow (*ROS*) events for climate change scenarios (A1B emissions scenario projected to 2025, 2055 and 2085) and observed occurrence of *ROS* events in the control time period (1972–2009; shown for reference in the top panel). Smoothed colored surfaces are from application of a local polynomial interpolation (LOESS). 'p25' and 'p75' are 25th and 75th percentile simulated values, respectively

Overall, the number of *ROS* events in a warmer climate will be greater at high elevations and fewer or the same at low to middle elevations. The seasonality of *ROS* events will also change in the future, with more events during winter, especially at high elevations. This is because a warming climate increases the elevation of the zero-degree isotherm. Our observations and projections indicate that, regardless of the amount of rain, changes in the frequency of *ROS* events is determined by trade-off between the reduced duration of snowpack (i.e. *SpD*) and the increased amount of precipitation that falls as rain (i.e. *S*:*R*), both of which are highly affected by temperature. A warmer climate would lead to a shorter snow season that involves a smaller number of annual *ROS* events; however, a warming climate also increases the elevation of the zero-degree isotherm, so more precipitation would fall as rain, thereby increasing the number of *ROS* events, especially during winter. Our results therefore agree with Leung et al. (2004), who observed an increase in the frequency of *ROS* events during winter for the Columbia River basin (western USA), but projected a decrease in *ROS* events under future climate conditions mainly because of shorter duration of snowpack. Based on our analysis of Switzerland, the shortening of the snow season will have a greater effect in such a trade-off for locations <2000 m a.s.l., where a decrease in *ROS* events is expected. At high elevations, the number of *ROS* events is more affected by changes in *S*:*R*, and we therefore project more *ROS* events during winter.

These conclusions are not necessarily definitive, because future changes in precipitation could have an effect. In particular, an increase in winter precipitation at low-to-middle elevations would lead to more *ROS* events and *ROS* events of greater magnitude. However, according to Fischer et al. (2015), RCMs do not produce a robust signal of increase for winter precipitation over Switzerland: in general terms, the intensity of precipitation is likely to increase in most Swiss territory; however, the frequency of precipitation events during winter will decrease, countering, in terms of precipitation sums, the effect of increasing intensity. Frequency of wet days is, on the contrary, projected to decrease during summer, and this would ultimately mean a reduction in ROS events at high elevations. However, according to Fischer et al. (2015), the regions at higher elevations will be less affected by this decrease in wet days during summer, as convective precipitation will still be important in the Alpine ridge.

It must be emphasized that our estimates are based on observations at ≤2700 m a.s.l., and 8% of Switzerland is above this elevation. The elevation-dependent response of snowpack to climate warming has been recently confirmed by Schmucki et al. (2015) through physical simulations in Swiss stations. They highlight that the warming projected by RCMs for the end of the present century will largely affect snow depth at low-to-middle elevations (~80% reduction in snow depth), and have little effect at high elevations (<25% reduction in snow depth). We did not extrapolate our estimates to these higher elevations, but according to Beniston (2012), snow cover may increase at elevations >3500 m a.s.l. by 2100, even in the presence of strong carbon emissions such as the IPCC (2007) A2 scenarios. Our approach also suggests that the shortening of the snow season under CC scenarios is mainly due to an earlier snowpack melt and depends less on the delayed start of the snow accumulation. However, recent physical simulations of snow duration in the eastern Swiss Alps that used a 3D snowpack model (Bavay et al. 2009, 2013) suggest that *BS* will be equally affected by warming, and possibly lead to even shorter snow seasons than suggested by our results.

This could change the sign or magnitude of our estimates for future *ROS* events. A further source of uncertainty that is not accounted for by our approach is the so-called 'elevation-dependent warming' (EDW) whereby high-mountain territories experience more pronounced warming than their lower elevation environments (Mountain Research Initiative EDW Working Group 2015). The linear mixed-effects model that we developed accounted, as a random effect, for the variance that the location of stations would introduce in the relationship between the duration of snowpack and the climate variables (mainly due to their differing elevations). This 'random effect' is, however, stationary; therefore it will not be totally valid when applying the model to future conditions, if any change involving this effect — such as that induced by the EDW — occurs. We believe, however, that the magnitude of such uncertainty for our model is minor, firstly because most studies for the Alps do not show a clear signal of EDW (see a review in Rangwala & Miller 2012) and secondly, because the range of elevations of the stations used in our model (900 to 2600 m a.s.l.) is not large enough to make such effect significant.

The probable increase in *ROS* events during winter at increasingly higher elevations may increase the frequency of floods and have other hydrological consequences. Although the percentage coverage of total area becomes increasingly smaller with increasing altitude, the surfaces located at higher elevations are still considered to play a crucial role in determining flood severity. At lower altitudes, although *ROS* events will likely become less frequent in the future, the increase in liquid precipitation and subsequent reduction of temporal snow storage that buffers runoff might also aggravate winter floods. These matters should be considered carefully for future hydrological planning in a country where flooding is a major issue (Weingartner et al. 2003, Köplin et al. 2014).

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