Changes of hydro-meteorological trigger conditions for debris flows in a future alpine climate

Kaitna, Roland; Prenner, David; Switanek, Matt; Maraun, Douglas; Stoffel, Markus; Hrachowitz, Markus

DOI
10.1016/j.scitotenv.2023.162227

Publication date
2023

Document Version
Final published version

Published in
Science of the Total Environment

Citation (APA)
Kaitna, R., Prenner, D., Switanek, M., Maraun, D., Stoffel, M., & Hrachowitz, M. (2023). Changes of hydro-meteorological trigger conditions for debris flows in a future alpine climate. *Science of the Total Environment*, *872*, Article 162227. https://doi.org/10.1016/j.scitotenv.2023.162227

Science of the Total Environment 872 (2023) 162227

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Changes of hydro-meteorological trigger conditions for debris flows in a future alpine climate

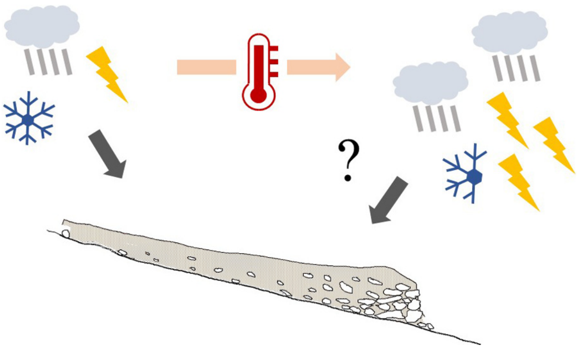
Roland Kaitna [a,*], David Prenner [a], Matt Switanek [b], Douglas Maraun [b], Markus Stoffel [c,d,e], Markus Hrachowitz [f]

[a] Institute of Mountain Risk Engineering, University of Natural Resources and Life Sciences Vienna, Austria
[b] Wegener Center for Climate and Global Change, University of Graz, Austria
[c] Institute for Environmental Sciences, University of Geneva, Switzerland
[d] Department F.-A. Forel for Environmental and Aquatic Sciences, University of Geneva, Switzerland
[e] Department for Earth Sciences, University of Geneva, Switzerland
[f] Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, the Netherlands

HIGHLIGHTS

- Climate change alters the hydro-meteorological trigger patterns for debris-flow initiation in the Austrian Alps.
- Changes are regionally different.
- Trend to occur earlier in the year.
- Snow-melt related triggers may become more frequent.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Ouyang Wei

Keywords:
Debris-flow initiation
Climate change
Trigger conditions
Hydrological modeling

ABSTRACT

Debris-flow activity is strongly controlled by hydro-meteorological trigger conditions, which are expected to change in a future climate. In this study we connect a regional hydro-meteorological susceptibility model for debris flows with climate projections until 2100 to assess changes of the frequency of critical trigger conditions for different trigger types (long-lasting rainfall, short-duration storm, snow-melt, rain-on-snow) in six regions in the Austrian Alps. We find limited annual changes of the number of days critical for debris-flow initiation when averaged over all regions, but distinct changes when separating between hydro-meteorological trigger types and study region. Changes become more evident at the monthly/seasonal scale, with a general trend of critical debris-flow trigger conditions earlier in the year. The outcomes of this study serve as a basis for the development of adaption strategies for future risk management.

1. Introduction

Debris flows are rapidly flowing mixtures of unsorted sediment and water in headwater channels of mountain landscapes, which regularly pose a threat to settlements and infrastructure in densely populated areas (Dowling and Santi, 2014). These *landslides of the flow type* (Hungr et al., 2001) are initiated by a critical combination of abundant sediment, steep inclination, and water (Rickenmann, 2016). The latter is mostly provided by rainfall, leading to slope failure- or runoff-generated debris flows (e.g. McGuire et al., 2017; Berti et al., 2020). The triggering rainfall can range from convective storms to stratiform precipitation (e.g. Borga et al., 2014; Prenner et al., 2019). Sometimes, intensive snow-melt or rain-on-snow events play a significant role in debris-flow initiation (e.g. Decaulne et al., 2005; Mostbauer et al., 2018). Since the work of Caine (1980), several studies focused on the identification of critical rainfall characteristics for the

---

* Corresponding author at: Peter Jordan Strasse 82, 1190 Vienna, Austria.
E-mail address: roland.kaitna@boku.ac.at (R. Kaitna).

http://dx.doi.org/10.1016/j.scitotenv.2023.162227
Received 13 November 2022; Received in revised form 18 January 2023; Accepted 9 February 2023
Available online 14 February 2023

initiation of shallow landslides and debris flows (e.g. Guzzetti et al., 2008; Berti et al., 2012; Marra et al., 2017), but it has been shown that including the hydrological history of a system can improve predictions (e.g. Wilson and Wieczorek, 1995; Prenner et al., 2018; Uwihirwe et al., 2020).

In the context of climate change, the questions arise how changing temperature and precipitation patterns together with the associated changes in hydrological regimes (Hanus et al., 2021) affect the frequency and/or magnitude of debris flows (Jomelli et al., 2007, 2009; Stoffel and Huggel, 2012) and consequently whether there is the societal need for adaption (Fuchs et al., 2017). For some alpine catchments there is evidence for increased debris-flow activity during the past decades (e.g. Dietrich and Krautblatter, 2017), for other sites there is no evidence for an increase (e.g. Stoffel et al., 2005). Despite of an increasing trend of meteorological indices of critical trigger conditions, a recent database-study found no clear trend of damage-inducing torrential flooding (including debris flows) in the Austrian Alps (Schloegl et al., 2021). The authors attribute this to a compensating and aggregated effects of the increasing number of technical mitigation measures.

A common assumption in the assessment of landslide and debris-flow activity is that a future climate with increased temperatures can hold more water in the atmosphere, which in turn can result in more intense rainfall events (Allen and Ingram, 2002; Trenberth et al., 2003) that may trigger such mass movements (IPCC, 2014; Gariano and Guzzetti, 2016). For all CO_2 – emission scenarios, climate models project an increase of temperature and changes in seasonal precipitation patterns in the European Alps, with a general trend of rainfall decreases in summer, especially in the southern regions, and increases in winter (Gobiet et al., 2014; Broennimann et al., 2018). In low- to mid-elevation areas, increased temperatures will lead to a decrease of the snow-precipitation ratio in winter (Berghuijs et al., 2014). There is indication that exceptional weather situations like the unusual warm and wet January 2018, with repeated rain-on-snow events causing landslides and debris flows, may become more frequent in the European Alps by the end of the twenty-first century (Stoffel and Corona, 2018). While Turkington et al. (2016) expect a limited annual change of debris-flow activity for two regions in France and Italy, Jomelli et al. (2009) conclude that the number of hillslope debris flows at the Massif des Ecrins (French Alps) might decrease after 2070 due to a projected decrease of rainfall events as well as the decrease of potential sediment-source areas by about 20 %, which is associated with reduced sediment production in high altitudes and an increase in the elevation of the tree line in a milder climate. For Switzerland, Stoffel et al. (2014) expect a shift of the debris-flow activity from summer to the “shoulder” seasons (i.e. away from summer to spring and fall). Decreasing precipitation frequency in future summers will facilitate sediment accumulation in the channels, thereby enhancing debris-flow probability later in the season. For the well-monitored Illgraben catchment in the Swiss Alps, projected changes of precipitation and air temperature may lead to a reduction of sediment production by physical weathering and hence debris-flow occurrence by >20 % by the end of the century (Hirschberg et al., 2020). An assessment of the impact of climate change on debris-flow activity in the Austrian Alps has so far only been analyzed and quantified by a life-cycle case study on the effect of mitigation measures compared to changes of debris-flow magnitude-frequency relationship due to climate change (Ballesteros-Cánovas et al., 2016).

In this study, we make use of a previously developed probabilistic susceptibility model (Prenner et al., 2018) that differentiates between hydro-meteorological trigger types to quantify the impact of climate change on debris-flow trigger conditions in six contrasting regions in the Austrian Alps. Specifically, we use the output of a process-based rainfall-runoff model that has been calibrated over 40+ years to identify hydro-meteorological pattern associated with past debris-flow occurrence in respective sub-catchments and assess changes of frequency and seasonality of such pattern under a projected future climate. Climate change projections are based on EURO-CORDEX simulations (Jacob et al., 2014), which have been post-processed by a novel two-step approach combining a trend-preserving bias adjustment (Switanek et al., 2017) and a spatial stochastic downscaling to the station scale. We combine these novel models for the first time to address specific research questions at the intersection between climate change modeling and hydro-geologic impact assessment:

- Will debris-flow triggering hydro-meteorological conditions across the Austrian Alps become more frequent in a future climate?
- Are there seasonal and regional differences in how trigger conditions change?
- What are possible consequences for future debris-flow activity in the Austrian Alps?

2. Study regions and data availability

The assessment of climate-change impacts on the hydro-meteorological susceptibility for debris-flow initiation was carried out for six contrasting river catchments, in which debris flows have regularly occurred in the past. The study regions range from high-elevation valleys north and south of the main Alpine divide, to lower elevations on the eastern edge of the Austrian Alps (Fig. 1). The several hundreds of torrential catchments within the six study regions span from heavily forested watersheds larger 10 km^2 to steep, mostly unvegetated catchments smaller than 1 km^2 with a high fraction of exposed bedrock. Hence, debris-flow initiation in respective catchments is associated with sediment-limited as well as sediment-unlimited conditions. Damaging earthquakes with an intensity >8° of the European Macroscopic Scale occur with a return period of only 120 years (source: www.zamg.ac.at) and are considered of minor relevance for debris-flow occurrence in the study regions.

Climatic conditions in the study regions are dominated by an oceanic climate in the west, a Mediterranean climate in the south and a continental climate in the east (Brunetti et al., 2009). These influences are reflected in the distribution of precipitation with highest annual rainfall sums in the western-most region Montafon with 1548 mm yr^{-1} and the smallest in the eastern-most region Feistritztal with 910 mm yr^{-1}. Long-term average runoff coefficients decrease from west to east as well. While ~80 % of the precipitation is released as stream flow in the Montafon, Pitztal and Defereggental, the lowest runoff coefficient, which does not exceed 40 % characterizes the easternmost Feistriztal. The reason for this decreasing trend is the decline of bare rock and sparsely vegetated areas in high-alpine regions at expense of forests and grasslands that enhance the retention capacities in the lower-alpine regions. The highest number of days with observed debris-flow activity were documented in the region Montafon (43 days between 1953 and 2013), and the smallest number in the region Feistritztal (3 days between 1975 and 2013). A detailed overview of catchment characteristics, data availability and modeling periods is given in Table 1.

3. Methodology

3.1. Experimental design

In this study we feed a semi-distributed implementation of a process-based, conceptual hydrological model with 28 bias-adjusted and downscaled climate change projections on a daily basis until 2100 (Switanek et al., 2022) (Fig. 2). The hydrological model was previously calibrated and exhaustively tested for the six study regions in the Austrian Alps over a period of 40+ years (Prenner et al., 2018, 2019). The model output time series of hydro-meteorological variables of the historical reference period (1971–2000) as well as for the near future (2021–2050) and the far future (2071–2100; cf. Hanus et al., 2021) of the same temporal-spatial resolution are subsequently fed into a regional susceptibility model for debris flows (Prenner et al., 2018) that differentiates between the meteorological trigger types “long lasting rainfall” (LLR), “short-duration storm” (SDS), “snow melt” (SM) and “rain-on-snow” (RS). By accounting for uncertainties that arise from the various climate projections and the hydrological model implementation we subsequently assess the change of frequency of days susceptible to debris flows in the six study regions and analyze regional

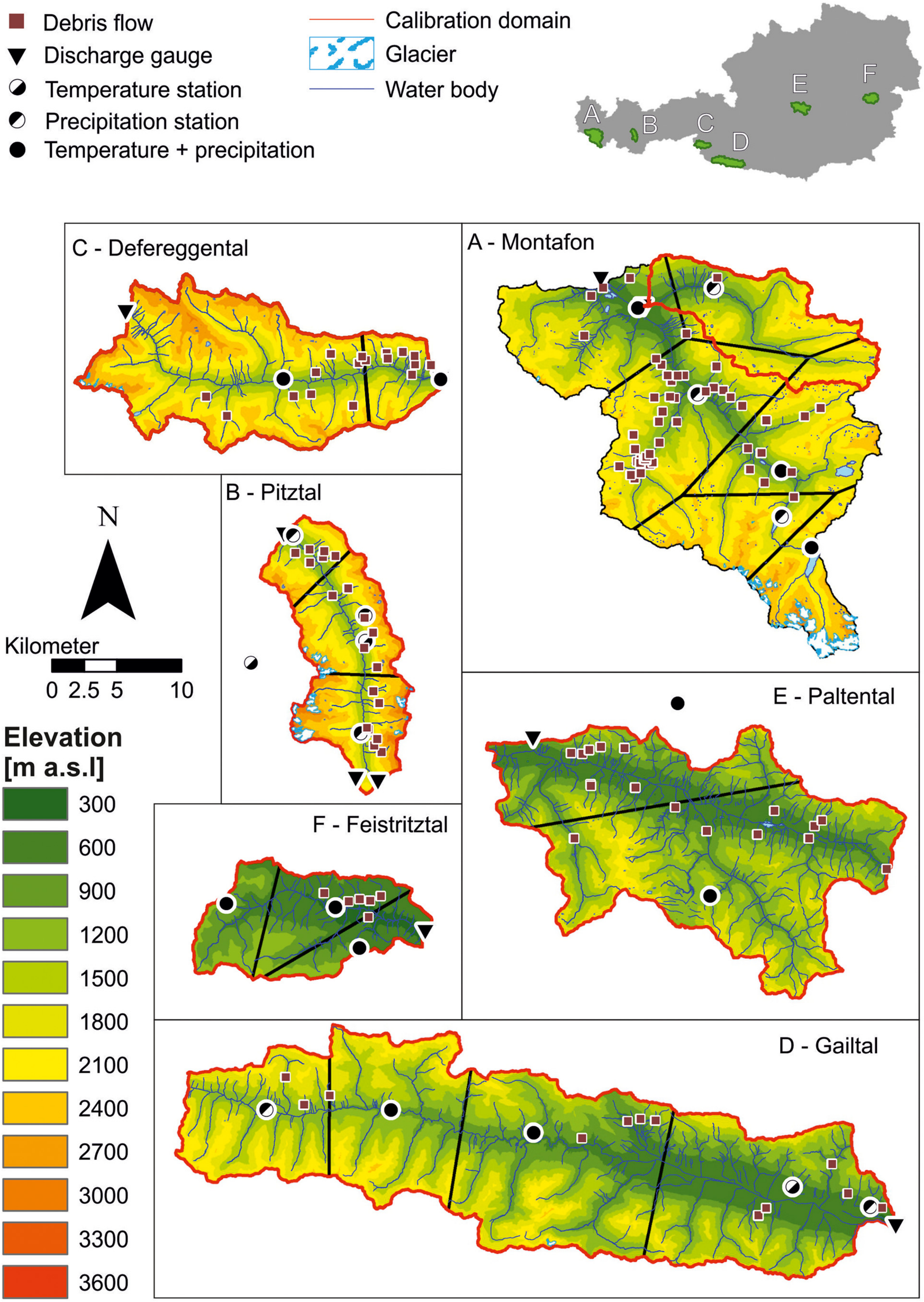


Fig. 1. Overview on the six study regions (west to east): Montafon, Pitztal, Defereggental, Gailtal, Paltental, Feistritztal including elevation, glacial zones, debris-flow occurrence, weather stations (precipitation and temperature), discharge gauge, drainage system and precipitation zones (= area of influence for each rain station).

Table 1
Overview of catchment characteristics, available data as well as modeling period, calibration period and validation period for each study region.

	Montafon	Pitztal	Defereggen-tal	Gailtal	Paltental	Feistritztal
Area [km^2]	510	133	222	586	368	115
Precipitation stations [#]	6	3	2	4	2	3
Elevation range (mean elevation) [m a.s.l.]	631–3312 (1877)	1093–3527 (2238)	1095–3398 (2171)	596–2780 (1477)	634–2446 (1316)	451–1593 (918)
Annual mean precipitation [mm]	1548	1151	1300	1410	1337	910
Annual mean runoff coefficient [−]	0.79	0.78	0.79	0.67	0.63	0.38
Fraction bare rock/Sparsely vegetated (Glacier share) [%]	31 (2)	51 (3)	39 (0.2)	7 (0)	2 (0)	0 (0)
Fraction grassland [%]	39	26	30	33	48	24
Fraction forest [%]	26	22	28	57	46	71
Fraction riparian zone [%]	4	1	3	3	4	5
Study period with available measurement data	1953–2013	1967–2013	1945–2016	1950–2013	1961–2013	1957–2013
Calibration period	1976–2011	1986–2010	1982–1986	1976–2005	1976–1999	1995–2011
Validation period	2012–2013	2011–2012	1987	2006–2007	2000–2001	2012–2013
Debris-flow event days [#]	43	13	10	10	12	3

and seasonal changes of the different trigger types. For the reader's convenience, we here summarize the background of climate projections as well as the hydrological model and the trigger model.

3.2. Climate projections

Projected station data were derived from regional climate simulations from the EURO-CORDEX initiative (Jacob et al., 2014, 2020). These EURO-CORDEX simulations dynamically downscale global climate projections for Europe from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012). Regional climate models (RCM) are used to downscale climate projections from the original global climate models (GCM) resolution to a common grid size resolution of 12.5 km for the European continent (Jacob et al., 2014). Recent research has identified severe artefacts when attempting to use bias adjustment as a simple statistical downscaling (Maraun, 2013; Maraun et al., 2017). We therefore apply a novel approach that separates the adjustment from the downscaling: The regional EURO-CORDEX projections were first bias adjusted against gridded reference observations and then further downscaled to the weather monitoring stations by a spatial stochastic downscaling model using daily observational measurement data from the respective stations (Switanek et al., 2022). The bias adjustment is conducted with SDM (Switanek et al., 2017). The stochastic downscaling approach is based on a transformed truncated Gaussian model and models the marginal distribution as well as the spatial correlation, of all of the nearby weather stations, separately for each study region. This ensured that the projected data for a weather station on an arbitrary day is consistent to that of the other stations in the same region. The model performs excellent for a range of diagnostics representing marginal, temporal and spatial aspects for moderate and extreme precipitation. Methodological details about the stochastic downscaling method as well as a comprehensive evaluation can be found in Switanek et al. (2022). That study demonstrated good performance at simulating mean and intense precipitation, dry- and wet-day probabilities, spatial correlations and spatial dependence of extreme rainfall for the catchments addressed in the study at hand.

The projections were run from 1970 to 2100. The bias adjustment and the stochastic model were calibrated to observations over the period from 1971 to 2000.

To represent different possible evolutions of future greenhouse gas concentrations, we have considered two representative concentration

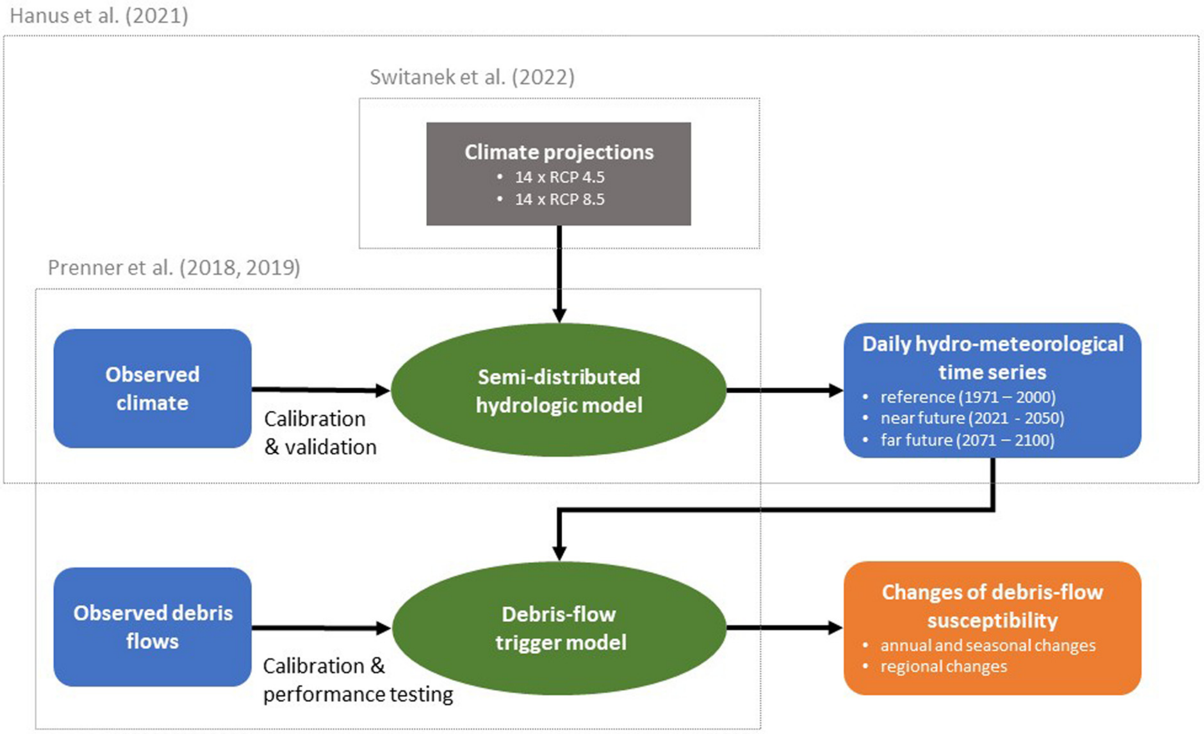


Fig. 2. Flowchart of the study design separately applied to all six study regions (inspired by Hirschberg et al., 2021).

pathways (RCPs) (Van Vuuren et al., 2011). These RCPs approximately prescribe the radiative forcing resulting from additional greenhouse gases such as CO2. For this study we use the scenario RCP4.5, representing mitigation efforts beyond current policies which assumes an additional forcing of 4.5 W m^{-2} by the end of the century, and, as a rather unlikely worst-case scenario, RCP8.5, with an additional forcing of 8.5 W.m^{-2} (Hausfather and Peters, 2020).

Each RCP scenario consists of an ensemble of 14 different combinations of GCMs and RCMs from the EURO-CORDEX initiative (Jacob et al., 2014; Jacob et al., 2020). The different models differ mainly in the resolution of the driving GCMs and the implementation of sub-grid processes, and are intended to sample our epistemic uncertainty about future regional climate change (Doblas-Reyes et al., 2021). The GCM/RCM combinations used in our study are displayed in Table 2.

Each of the 14 climate models of the ensemble was run for both RCPs, resulting in 28 projected time series for each rain and temperature station from 1970 to 2100 available for hydrological modeling. To assess changes, we define three periods. The historical period from 1971 to 2000 serves as reference period. Our current and immediate future period (2021 to 2050) we term “near future”. The period 2071 to 2100 we term “far future”.

3.3. Hydrological model

The process-based hydrological model operates on a precipitation zone-scale, which allows estimates of water storage and flux in different compartments of the hydrological systems of the study regions and ensures the processing of precipitation information on the highest available spatial level. We use a Thiessen polygon decomposition based on the location of the available rain gauges (Fig. 1). The same applies for temperature data. Hydrological heterogeneity is considered by different hydrological response units (HRU) as suggested by Gao et al. (2014). We differentiate between bare rock/sparsely vegetated areas, forest, grassland and riparian zones. The elevation range of each HRU was discretized into elevation bands of 100 m to account for elevation gradients in precipitation and temperature based on the approaches of Sevruk (1997) and Rolland (2003), respectively. Glaciers in two out of six regions were assumed to occur in bare rock domains only and were simplistically modelled with unlimited water supply for their areal fraction in an elevation zone.

For the setup of the hydrological model a digital elevation model (DEM) with a grid size of 10 by 10 m (vogis.cnv.at), a Height Above Nearest Drainage map (Rennó et al., 2008) based on the DEM, the CORINE land-cover dataset from 1990 (https://www.eea.europa.eu), and a glacier distribution map (Patzelt, 2015) were used.

The model, run at a daily time step, was forced with precipitation and temperature data available from the Austrian Central Institute for Meteorology and Geodynamics (ZAMG) and calibrated to stream flow observations provided by the Hydrographic Service Austria (HD) and the hydropower companies Illwerke and TIWAG. For model calibration we applied the “DREAM” algorithm (Vrugt, 2016) to obtain posterior parameter distributions. DREAM was run for 20,000 generations for each study region using computational resources of the Vienna Scientific Cluster (VSC). Calibration periods ranged between 4 and 35 years and validation periods between one and two years, respectively (Table 1). Post-calibration model evaluation using various performance metrics demonstrated the model's ability to simultaneously reproduce multiple hydrological signatures. Detailed performance metrics are given in the Supplement 1 and Prenner et al., 2019. These results suggest that the model is a robust and plausible representation of the underlying processes.

Table 2
RCM-GCM model combinations used for providing the time series for hydrological modeling.

		RCM						
		ALADIN	CCLM	HIRHAM5	RACMO	RCA	WRF	Sum
GCM	CNRM-CM5	x	x			x		3
	EC-EARTH		x	x	x	x		4
	HadGEM2-ES		x		x	x		3
	IPSL-CM5A-MR					x	x	2
	MPI-ESM-LR		x			x		2
	Sum	1	4	1	2	5	1	14

To consider uncertainties of the hydrologic model, 25 different sets of the parameter's posterior distributions were sampled. The hydrological simulation was run with each model parameter set for each of the 28 projected precipitation and temperature station series. Hence, a total of 700 (=25 ∗ 28) projected future catchment state time series for each precipitation zone of all regions were available for the assessment of changes and uncertainties of trigger conditions. A validation of the hydrological model based on the modelled past climate carried out for the period 1981–2010 by Hanus et al. (2021) showed that seasonality of runoff and timing of extreme events are generally well captured, while the magnitude of high flows are somewhat underrepresented, mainly due to an insufficient representation of localized, high-intensity rainfall events as input data. Since the regional susceptibility model for debris flows (Section 3.4) relies on a combination of hydro-meteorological criteria, we assume that these short-comings have a minor effect on the performance of the model. In this study we isolate the effect of climate change and neglect land use changes or other anthropogenic factors like engineering mitigation measures against debris-flows. The hydrological simulation of projected climate data ranges from 1970 to 2100.

To test the statistical significance of identified changes, the Wilcoxon Rank Sum test (Wilcoxon, 1945) was applied to compare the value distributions of either future period (2021–2050 or 2071–2100) with the historical reference period (1971–2000). This test was carried out for each precipitation zone of a region which comprises 700 time-series of projected hydro-climatological catchment states. A significant change of the hydrological regime was assumed, when at least 50 % of the realized Wilcoxon tests for a region were significant at a 5 % significance level. In our definition, a significant positive or negative change occurred when at least 80 % of the significant samples showed deviations in the corresponding direction. Otherwise, when the significant samples did not show a distinct direction (below 80 % threshold) the uncertainty was assumed to be too large to outline a clear trend. This procedure was repeated for each of the two emission scenarios.

3.4. Trigger model

Debris flows can be triggered by different weather conditions, including steady rain in the course of low-pressure systems, convective precipitation, or even snow melt (e.g. Decaulne et al., 2005; Guzzetti et al., 2008; Mostbauer et al., 2018). There is evidence that the magnitude of a critical trigger event (i.e. rainfall) is not independent of the antecedent hydrological conditions (e.g. Bogaard and Greco, 2018; Maraun et al., 2022). Prenner et al. (2018) showed that different weather conditions leading to the initiation of debris flows are reflected in the signatures of daily time-series of measured and modelled hydro-meteorological parameters. For example, a long-lasting rainfall event (LLR) is typically associated with decreasing temperatures and increasing soil moisture on the days preceding a debris-flow event in the region. On the other hand, a convective “short-duration storm” (SDS) occurs when the landscape heats up, which is reflected in a decrease of soil moisture and an increase of temperature span during a day. Debris-flow events associated with snow melt (SM) occur on consecutive days of high soil moisture and intensive snowmelt. Prenner et al. (2018) developed a probabilistic forecasting model based on a combination of measured and modelled hydro-meteorological parameters that includes the hydrological causes related to the trigger and showed that the model outperforms rainfall-only approaches. On a regional scale, the advantage of such an approach is that data for calibration and validation is available over long time periods (40+ years) and the definition of a critical rainfall threshold is avoided, including all the limitations associated with that (e.g. Bogaard and Greco, 2018; Hirschberg et al., 2021). For the current study we apply a slightly modified set of trigger criteria as presented by

Table 3

Criteria and inequality equations for each trigger which have to be fulfilled that a catchment state counts as trigger condition. Please see the annotations for details about the criteria definition. (LB = Lower Bound, UB = Upper Bound).

LLR	SDS	SM	RS
Effective precipitation on the event day[a] ($LB \leq x \leq UB$)	Effective precipitation on event day[b] ($LB \leq x \leq UB$)	Effective precipitation on event day ($x = 0$)	Effective precipitation on event day ($1.0 \leq x$)
Normalized mean 3-day potential evapotranspiration[1] ($LB \leq x \leq UB$)	Normalized mean 3-day potential evapotranspiration[b] ($LB \leq x \leq UB$)	Snow melt on event day ($LB \leq x$)[d]	Snow line on event day[f] ($x \leq UB$)
3-day soil moisture change prior to event day[a] ($LB \leq x \leq UB$)	3-day soil moisture change prior to event day[b] ($LB \leq x \leq UB$)	Soil moisture on event day[e] ($LB \leq x$)	Soil moisture on event day[e] ($LB \leq x$)
Soil moisture on event day[a] ($LB \leq x \leq UB$)	Soil moisture on event day[b] ($LB \leq x \leq UB$)		
Snow melt on event day[c] ($x \leq UB$)	Snow melt on event day[d] ($x \leq UB$)		

[a] LB, UB represent the 5th and 95th percentile values derived from hydro-meteorological variables of the observed past on LLR triggered debris-flow event days.

[b] LB, UB represent the 5th and 95th percentile values derived from hydro-meteorological variables of the observed past on SDS triggered debris-flow event days.

[c] UB equals the 90th percentile of all snow melt values (above 0) of a precipitation zone.

[d] LB equals the 90th percentile of all snow melt values (above 0) of a precipitation zone.

[e] LB equals the 90th percentile of all soil moistures values of a precipitation zone.

[f] UB is equal to $[MAX(e) - MIN(e)] / 2 + MIN(e)$ of a study region where e is the elevation of the snow line.

Prenner et al. (2018) and separate between the trigger types long-lasting rainfall (LLR), short-duration storm (SDS), snow melt (SM), and rain-on-snow (RS) (Table 3).

The criteria for these trigger types were formulated according to the inequality notation $LB \leq x \leq UB$, where x is the value of a hydro-meteorological variable, LB the lower bound and UB the upper bound threshold (Table 3). LB and UB thresholds were determined for each precipitation zone separately. We identify days characterized by LLR and SDS trigger conditions based on the effective precipitation on the event day, the normalized mean 3-day potential evapotranspiration, the 3-day soil moisture gradient prior to the event day and the snow melt on the event day. LB and UB correspond to the 5th and 95th percentile values of hydro-meteorological variables on days in the past where at least one debris flow was observed within the respective region according to respective trigger type. Due to limited historical events in the Feistritztal (only 3 debris flows), LB and UB were computed as $m \pm 0.5^*|m|$, where m is the group mean of the event-day values of a hydro-meteorological variable. Though snow-melt and rain-on-snow trigger conditions were associated with <20 % of the past debris-flow events and hence hydro-meteorological footprints are less robust (Prenner et al., 2019), these trigger types may be of increasing importance for future winter and spring periods (Stoffel and Corona, 2018). A critical reflection about the selected criteria is provided in Section 5.1.

The trigger model was applied to each day of the 700 time-series representing future periods (either 2021–2050 or 2071–2100) as well as to each day in the historical reference period (1971–2000). All days that fulfill the criteria for a trigger (resulting in a “true” according to Boolean algebra) were assumed as a positive trigger condition. These days were counted up and normalized on an annual basis, both for the reference period ($\widehat{N}_R$) and future periods ($\widehat{N}_F$), respectively. The mean annual change of trigger-condition frequency ΔN for a future period with respect to the reference period was then computed with

$$\Delta N = \left(\frac{\widehat{N}_F + 1}{\widehat{N}_R + 1} \right) \times 100 \tag{1}$$

The increase of the numerator and denominator by the value 1 ensures the avoidance of divisions by zero. This analysis was carried out on a yearly as well as a monthly basis and for each emission scenario (RCP4.5 and RCP8.5) separately. A comparison with the trigger model fed with the observed modelled past is shown in Fig. S1 in Supplement 1.

4. Results

4.1. Change of climate conditions and hydrological catchment states

We here summarize changes of climatic conditions and hydrological variables, representing the hydrological catchment state, relevant for the assessment of days susceptible for debris-flow initiation. Fig. 3 exemplarily shows changes and variations of relevant hydro-meteorological parameters derived for the region Montafon for emission scenario RCP4.5. The outcomes of RCP8.5 and all other regions are given in Supplement 2. A detailed analysis of future changes of runoff in the respective regions is provided in the recent study of Hanus et al. (2021).

4.1.1. Changes of future climate

The ensemble of the 28 climate change projections consistently predicts a significant increase of mean air temperature in all regions and both emission scenarios for the near future as well as for the far future (Fig. 3 for the Montafon region, Fig. S1 in Supplement 2 for all regions). For the near future the average increase ranges between +1.4 °C and +1.7 °C for RCP4.5 and RCP8.5, respectively. For the far future +2.5 °C and +4.3 °C are projected. When averaging all RCP scenarios and periods over the year, warming is projected to be highest in the catchments Pitztal (+2.7 °C) and Defreggental (+2.6 °C) and lowest in the Paltental (+2.3 °C). The most pronounced warming is expected for the summer months, except for the Pitztal region where the highest rise is projected for January.

Due to the variation across climate models, precipitation patterns are not projected to statistically significantly change throughout the year in the study regions (Fig. S3). Only for a few months in the far future we expect a change in a certain direction (e.g. increase of precipitation for the Montafon region in June for emission scenario RCP4.5 (Fig. 3) and a decrease in August for RCP8.5). On average the climate model ensemble suggests that annual precipitation increases between 4 % and 9 %. On a seasonal basis we expect a slight increase during winter time (October to March) in all regions, emission scenarios and both future periods. During summer months, especially in August, mean precipitation tends do decrease in the far future for all regions.

The modelled potential evapotranspiration is strongly related to air temperature and enriched with information about incoming solar radiation (Hargreaves and Samani, 1982). Hence it peaks in summer and is lowest in winter. Not surprisingly, potential evapotranspiration rates show, similar to mean temperature, a significant increase for all regions (Fig. S4).

4.1.2. Changes of hydrological catchment states

Future soil moisture contents are expected to be significantly higher from January to March and, for the regions Montafon (Fig. 3), Pitztal, and Paltental, also in December (Fig. S8). This is caused by more precipitation falling as rain instead of snow as well as an earlier snow melt. During summer projected hydrological catchment states suggest a significant decrease of soil moisture during summer, especially in the regions south of the Alpine main ridge (Defereggental and Gailtal). In general, changes are more distinct (both, wetting and drying trends) in the far future than in the near future.

The actual evapotranspiration is expected to significantly increase in the two most western regions (Montafon and Pitztal) during the whole

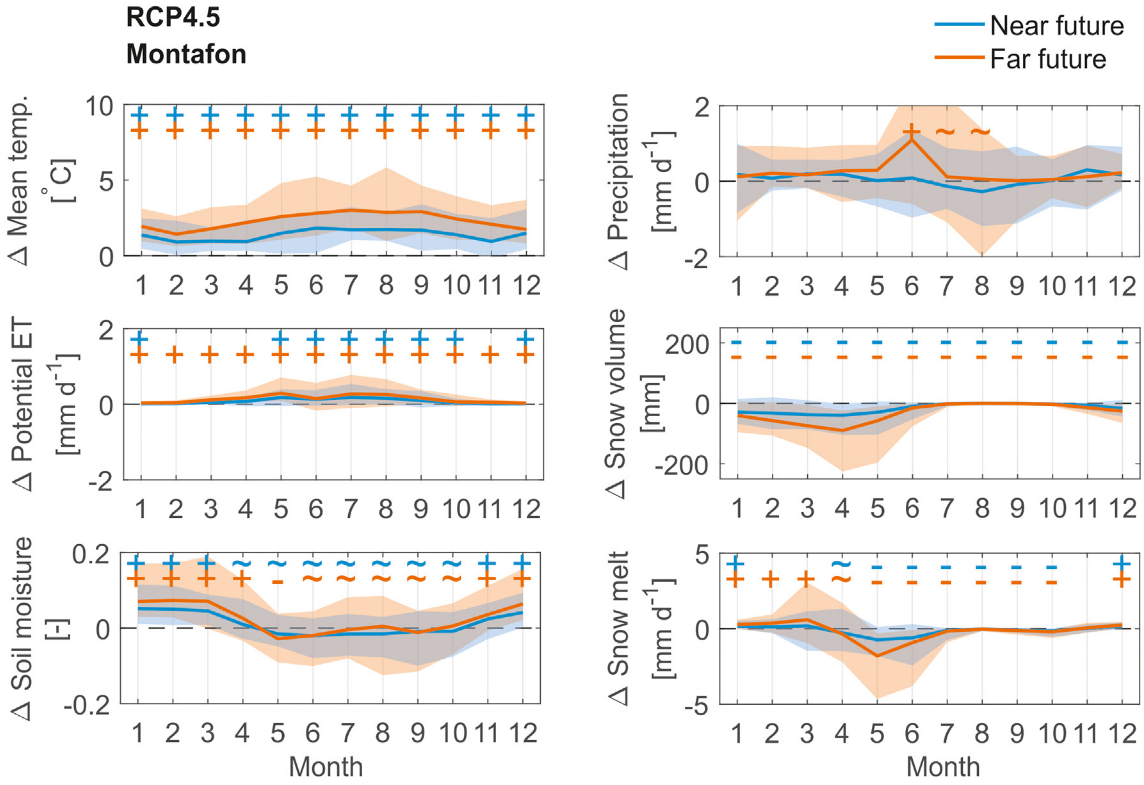


Fig. 3. Changes of climate conditions and hydrological catchment variables for the region Montafon for the emission scenario RCP4.5. Blue color represents the period 2021–2050 (near future) and red color the period 2071–2100 (far future). The markers "+", "−", and "~" indicate the significance of changes determined as explained in Section 3.3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

year, while an increase is only found in the winter half-year in the other four regions (Fig. S5). Here, the actual evapotranspiration does not achieve its full potential during the summer months because of limited available water in the soil. As a consequence, either no significant changes of mean actual evapotranspiration are obtained (e.g. near future for Gailtal and Paltental with RCP4.5) or no clear positive or negative trend can be detected (e.g. Defereggental for both scenarios and for the far future in the Gailtal region). However, a significant decrease of evapotranspiration (potential and actual) in a specific month is not predicted in any constellation.

Total snow volumes are expected to significantly decrease in all regions, for all future periods and all emission scenarios (Fig. S6). The expectations concerning timing, rate and duration of snow melt is more diverse (Fig. S7). Except for the lowest region Feistritztal, snow melt significantly increases in January and – especially for the high alpine regions Montafon (Fig. 3), Pitztal and Defreggental – in December, February and March. During mid and end of spring (April, May) snow melt rates decrease compared to the reference period. The major reason for this is the prediction of a higher snow line in future climate that restricts snow and snow melt to higher areas, which constitute only a small portion of the total precipitation zone. This effect oppresses the generation of melt rates comparable to the past.

4.2. Changes of debris-flow trigger conditions

4.2.1. Annual changes

Averaged over all study regions, all trigger types, we find that the relative changes of number of days with critical hydro-meteorological conditions range mostly within the modelled uncertainties, both for the near future and the far future (Fig. 4). When separating between trigger types, the model predicts that snow-melt related debris-flow events (SM and RS) will decrease in the far future for the RCP8.5 scenario, which is a consequence of the strong increase of temperatures >4 °C and the associated lower snow water volumes. For the other trigger types, scenarios and future periods, the number of days susceptible to debris flows show no significant changes on an annual basis.

When separating between the study regions, we find regional differences, reflecting the climatic and hydrological heterogeneity of the Alpine main ridge. The most distinct changes are predicted for the Paltental, a low-alpine region in the central to eastern part of Austria, and the Pitztal, a high-alpine valley in the western part. For the Paltental (Fig. 5a), the annual number of days susceptible to debris flows are expected to decrease by around −7 % (−4.3 d yr^{-1}) for emission scenario RCP4.5 and by 4 to 14 % (−2.5 to −5.7 d yr^{-1}) for RCP8.5. Responsible for these comparatively large changes are a decreasing number of days fulfilling the criteria for SDS (−7 to −17 %) followed by LLR trigger conditions (−3 to −18 %). The number of events triggered by SM and RS conditions are expected to remain unchanged. Almost no changes were computed for Feistritztal, which is located even more east than Paltental. Here, debris-flow events were mostly absent in the past as they will be in the projected future (Fig. S9).

An opposite expectation we derive for the Pitztal region (Fig. 5b). Here, weather conditions indicating LLR events show an increase in the far future, both for RCP4.5 (+6.2 %) and RCP8.5 (+11.9 %), corresponding to an annual change of 1.5 d yr^{-1} in RCP4.5 and 2.7 d yr^{-1} in RCP8.5. Due to shorter snow cover duration by the end of the century, snow-melt related events are expected to decrease (−13.7 % or −2.3 d yr^{-1}in RCP8.5). The projected changes of debris-flow initiation by SDS, which is the trigger type that was responsible for >50 % of the documented events in the past (Prenner et al., 2019), show a strong variation, especially for the future. For the Paltental and the Defereggental there is a tendency of reduction, for both future periods and emission scenarios.

For the study regions south of the Alpine main ridge (Defereggental and Gailtal), we find the most distinct changes for snow-related trigger conditions, with decreasing signals especially for the far future in RCP8.5

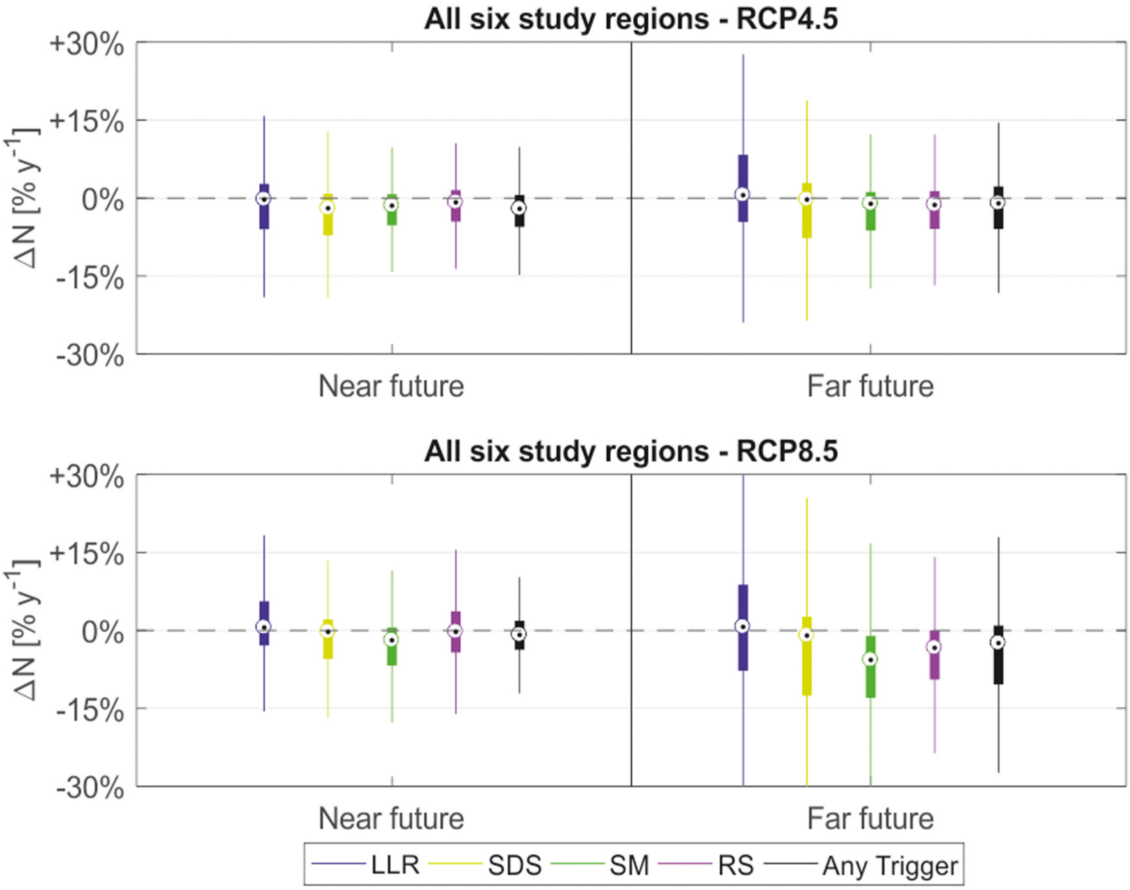


Fig. 4. Annual change of trigger conditions (LLR, SDS, SM, RS as well as without trigger differentiation) frequency for the near and far future period and emission scenarios RCP4.5 and RCP8.5. ΔN is the mean annual change of trigger-condition frequency for a future period with respect to the reference period.

(Fig. 5c and d). Only for the Gailtal region, LLR conditions may slightly increase by the end of the century. For the most western region Montafon and the most eastern region Feistritztal we do not find substantial changes on an annual basis (Figs. S9 and S10).

4.2.2. Seasonal changes of trigger conditions

Making use of the daily resolution of projections, we evaluate changes of days susceptible to debris flows on a monthly basis. Though the relative importance of trigger types varies throughout the year, results show a strong seasonality of projected changes.

For long-lasting rainfall (LLR) conditions that triggered debris flows in the past, we find a median increase of susceptibility especially for the most western regions Montafon (Fig. 6a) and Pitztal (Fig. 6b) from March to June, with maximum increases in April of up to 50 % for emission scenario RCP8.5. It is important to note that this effectively corresponds to an increase of 1–2 d yr^{-1} and infers the expectation that in a future climate debris flows due to LLR events will occur earlier in the year. This pattern is even more pronounced in the southern-most region Gailtal, with events as early as February and March (Fig. 7a). For the months July, August and September, LLR trigger conditions decrease across most regions (in the region Paltental up to −40 % in August in the far future of RCP8.5, corresponding to 2 d yr^{-1}, Fig. S11). In late fall, the situation is more diverse. While in the regions Pitztal and Gailtal future LLR conditions become more frequent towards the end of the year, the other regions show no signal.

Results of the current study suggest that the period with SDS trigger conditions will be prolonged in the future. Although the highest convective potential is typically reached during the summer months, results suggest a decrease of frequency, up to −30 % for August in the far future of RCP8.5 in the Paltental. This decrease tends to be larger compared to the decrease of LLR conditions.

For spring, increases of SDS conditions are projected for April and – in the three western regions Montafon, Pitztal and Defereggental (Figs. 6a, b and 7b) – also for May. Frequency changes are most distinct for the region Gailtal, which is located south of the Alpine chain. Here, a considerable extension of SDS conditions are projected for December to March, with highest increases in February with >50 % (Fig. 7a). To put this number into perspective it has to be kept in mind that winter thunderstorms leading to debris flows have been rare in the past and this increase corresponds to an effective absolute increase of only 5 d yr^{-1}.

In the future the amount of precipitation that falls as snow will be significantly lower due to higher temperatures (Figs. S2 and S3). Throughout all regions, emission scenarios, and future periods, we detect rising number of days with rain-on-snow conditions (RS) for about six months of the year, while snow-melt conditions (SM) increase for four months of the year. The susceptibility to RS conditions begins in November in high-alpine regions Montafon, Pitztal and Defereggental as well as in the low-alpine region Paltental. The RS condition frequency increases highest in the Paltental at the end of the winter season (up to +47 % in March, Fig. S11 in Supplement). In contrast, RS conditions in the Montafon increases in core winter time (January and February) by up to +13 % (Fig. 6a). Only minor increases (+3 %) are observed in the southern Gailtal region (Fig. 7a). The largest reduction of RS conditions occurs in the Pitztal by about −40 % (Fig. 6b). For all projections, SM conditions generally shift to times earlier in the year. For the far future in the worst-case scenario RCP8.5, there is a rise of critical SM conditions in February (+26 % in Montafon), March (+10 % in Paltental) and April (+36 % in Pitztal) and a decrease in May (−57 % in Gailtal and −35 % in Paltental) and June

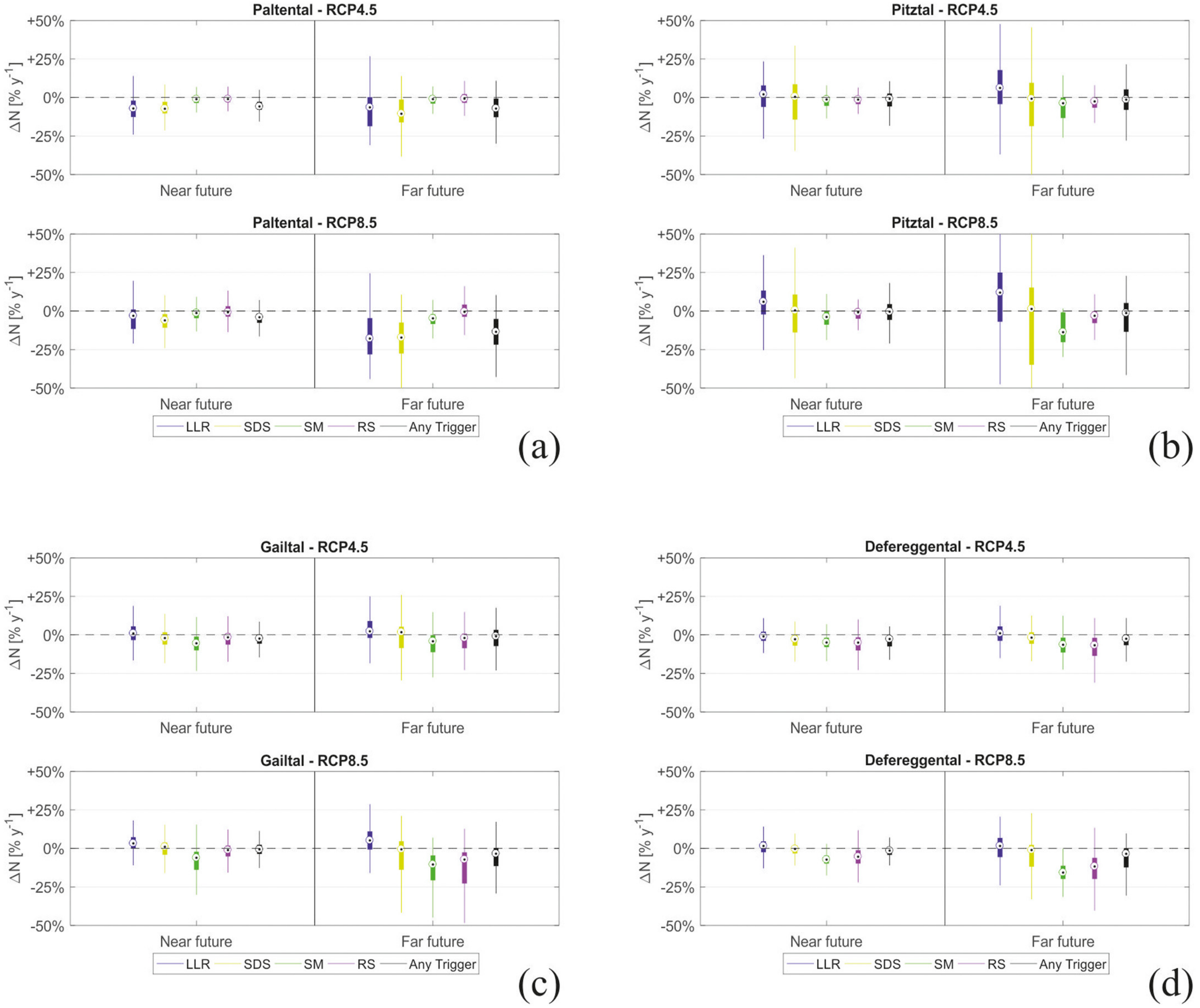


Fig. 5. Annual change of trigger type frequency (LLR, SDS, SM, RS as well as without trigger differentiation) for the near and far future period and emission scenarios RCP4.5 and RCP8.5 for the study region Pitztal (a), Paltental (b), Defereggental (c), and Gailtal (d). ΔN is the mean annual change of trigger-condition frequency for a future period with respect to the reference period.

(−55 % in Pitztal). Within a large part of the year, there is no change of SM conditions due to a missing snow cover to generate large melt intensities on the precipitation zones for all regions.

5. Discussion

5.1. Uncertainties and limitations

The outcomes of this study are associated with manifold uncertainties from multiple sources, which is a general and well-known limitation in hydrologic modeling (Beven and Lamb, 2017) and climate change impact assessment (Clark et al., 2016). To a certain part, these uncertainties stem from the available measured hydrological input data (epistemic uncertainties), which are unavoidable, especially when there is a relevant snow fraction (Parajka et al., 2005). An additional challenge is the fact that in high mountain areas precipitation and temperature can exhibit considerable spatial heterogeneity, which is often typically not well-captured by monitoring stations (Hrachowitz and Weiler, 2011). We tried to limit the effects of the above by splitting the regions into hydrological response units and compensate the lack of elevation-resolved input data by accommodating temperature and rainfall data for 100 m elevation bands based on lapse rates derived for the alpine region by Sevruk (1997) and Rolland (2003).

Another source of uncertainty comes from modeling itself. As a general problem underlying all applications of hydrological model, hydrological processes and fluxes in the study catchments are assumed to be represented by the structure and parametrization of the underlying hydrological model, which, although providing plausible response dynamics when confronted with available data, cannot be fully verified due to the lack of sufficiently detailed data (e.g. Beven et al., 2018).

Uncertainties are also associated with the time series of possible future climates. Obviously, the future development of CO_2 emissions or the technological progress are unknown. Subsequently, there is a chain of uncertainties related to global and regional climate modeling and downscaling approaches (Clark et al., 2016). For this study, we focus on scenarios which we consider to represent the upper (RCP8.5) and lower bound (RCP4.5) of possible concentration pathways.

Changes in regional rainfall, in particular of extreme events, are affected by substantial uncertainties about the large-scale atmospheric circulation

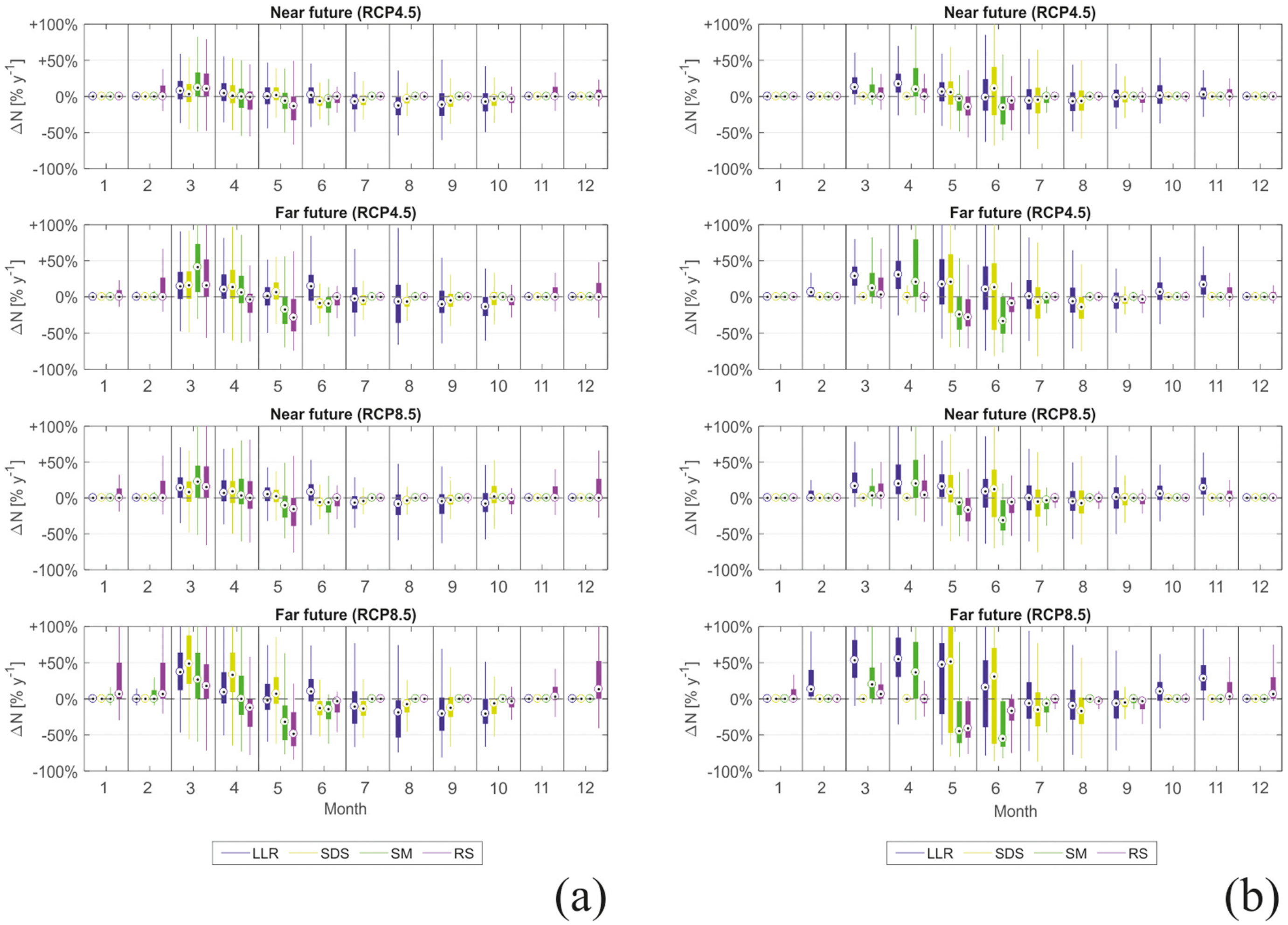


Fig. 6. Seasonal change of trigger type frequency (LLR, SDS, SM, RS) for the regions (a) Montafon and (b) Pitztal for the near and far future and emission scenarios RCP4.5 and RCP8.5. ΔN is the mean annual change of trigger-condition frequency for a future period with respect to the reference period.

(here represented by GCMs) as well as local – often convective – processes and the influence of the complex topography, which is only coarsely represented even in the chosen RCMs. Additionally, internal variability strongly affects climate projections, in particular for the near future (Doblas-Reyes et al., 2021). The use of a state-of-the-art climate model ensemble allows us to comprehensively sample uncertainties, but in particular changes in local processes may not be well captured by the ensemble spread. The downscaling to the station scale is represented by a single model described by Switanek et al. (2022).

As detailed in the methods section, we have accounted for the uncertainties of the hydrological modeling by sampling 25 parameter sets of the parameter posterior distributions stemming from the probabilistic model calibration. Each of these 25 parameter sets were then applied to each of the 28 climate projections, which cover an ensemble of 28 model scenarios based on two emission scenarios. We assume that the resulting 700 time-series of future hydrological catchment states provide a broad representation of the range of combined uncertainties of the hydrological and climate model.

The debris-flow trigger model relies on criteria identified by Prenner et al. (2018). A strength of this method is (1) that it differentiates between hydro-meteorological trigger types, (2) the criteria associated with these trigger types are connected to the hydro-meteorological signature and history of the catchment, which can be captured on a daily basis, and (3) that the calibration period covers long time scales (40+ years). A similar indirect approach was carried out by Turkington et al. (2016), who used a combination of convective available potential energy (CAPE) and specific humidity as a proxy to capture the atmospheric conditions favoring debris-flow initiation in a future climate. For our study predictions are made on a regional scale rather than on the scale of each individual locations (e.g. gullies), where debris flows actually initiate as in studies focusing on specific torrential catchments (e.g. Rengers et al., 2016; Bernard and Gregoretti, 2021; Oorthuis et al., 2022). This is a trade-off between resolution and data availability, but also guarantees that the model chain (climate-hydrology-trigger) is kept on the same scale. The main challenge for building a more general and detailed trigger model is the limitation of historical data on debris flows, water fluxes together with temporal variations of sediment availability (e.g. as a function of sediment production and connectivity). This limited sample size only warrants rather simple, low-dimensional models in order to avoid the adverse effects of an over-parameterized susceptibility model. In other words, building a more detailed regional susceptibility model will include more prediction variables than can be meaningfully calibrated with the observations available. Future studies need to work out and test strategies for a more general model, ideally including geomorphological components, as developed for the catchment-scale studies of Bennett et al. (2014) and Hirschberg et al. (2020). We consider the current study, which focuses on a regional scale, as a first step in this direction.

A further limitation is that upper and lower bounds of threshold trigger criteria were derived from (usually extreme) catchment states at debris-flow occurrence in the past, whereas the criteria sets were applied to both, projected future and past. Hence, results shown in this study are conditional on the assumption that the pattern pointing to debris flows in the

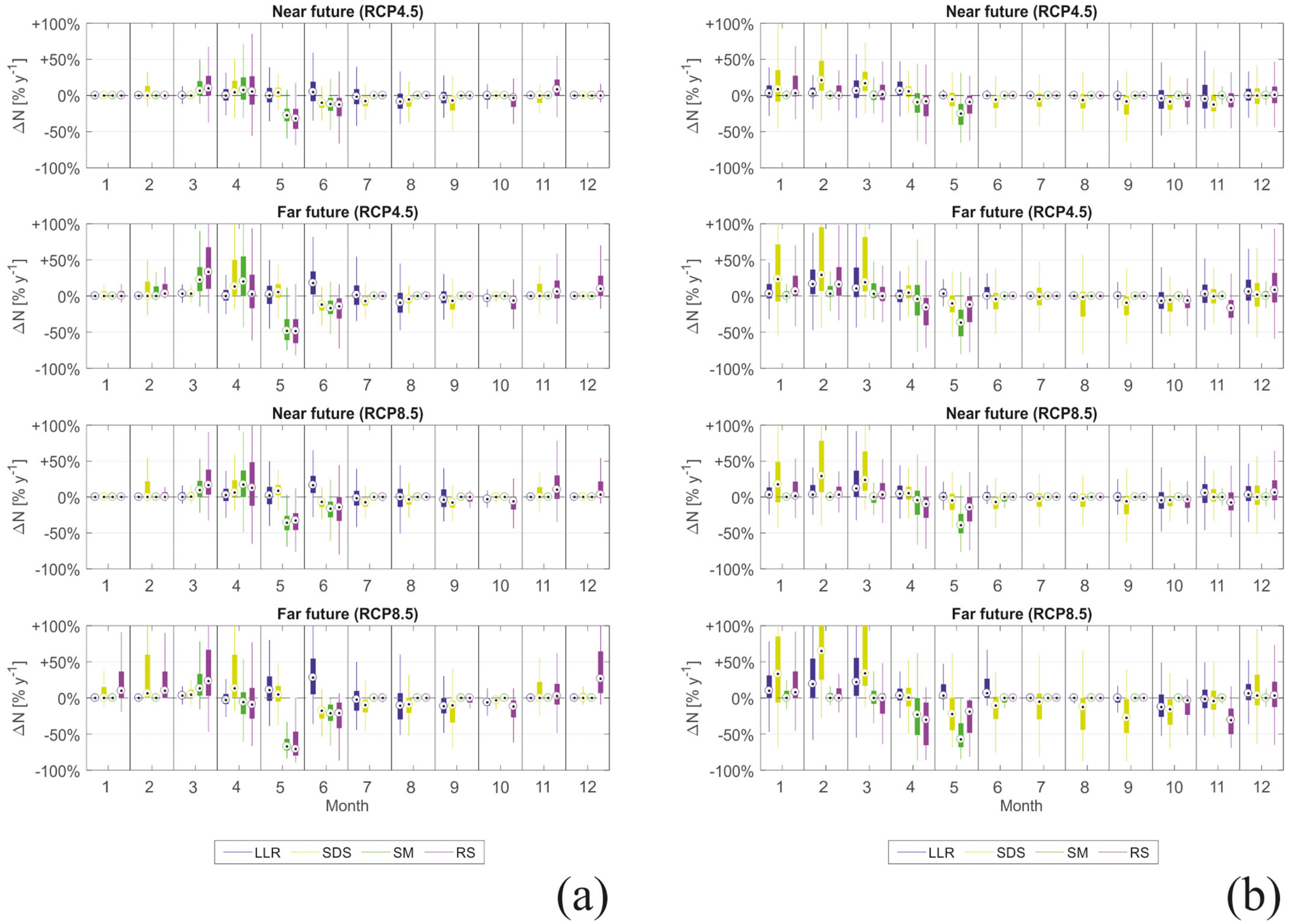


Fig. 7. Seasonal change of trigger type frequency (LLR, SDS, SM, RS) for the regions (a) Gailtal and (b) Defereggental for the near and far future and emission scenarios RCP4.5 and RCP8.5. ΔN is the mean annual change of trigger-condition frequency for a future period with respect to the reference period.

past will also hold in the future. This may introduce some bias especially when dealing with the far future where trends from climate change in hydro-meteorological variables are largest. For example, due to rising air temperatures, future debris-flow events will generally occur within a warmer environment. Applied trigger criteria on future days will mark rather insignificant days instead of the extreme days because those may be outside of the LB and UB boundaries. To counteract this effect, the mean 3-day potential evapotranspiration (used as criterion for LLR and SDS and which is strongly related to air temperature) was normalized by the mean value over the concerned 30-year period to remove this trend. Instead of normalizing the potential evapotranspiration, an alternative option would have been to remove the UB of the criteria inequality equations so that every magnitude greater than LB would count as trigger condition. However, in that case, LB would remain unadjusted for future periods, thus this approach was discarded.

A similar challenge is the definition of an UB condition for the rainfall criteria for LLR and SDS trigger types, as the trigger model might miss days susceptible to debris flows outside the upper bound (i.e. future extreme rainfall events). The main arguments for keeping an UB condition are that we aim to assess how hydro-meteorological conditions associated with the triggering of debris flows in the past will change due to climate change and that defining an UB condition enables a better differentiation between LLR and SDS trigger types. Additionally, in the absence of an UB condition, the rainfall criteria would be obsolete, as the 5th percentile that defines the lower bound is mostly close to zero for the SDS trigger type, as short duration storms are typically very local phenomena and not captured by rain gauges in the main valley axis. We assume the this may affect the detailed results, but not the overall interpretation.

5.2. Changes of debris-flow activity

The hydrological response of our study regions changes significantly by changing temperature and precipitation patterns in a future climate, which is in accordance to the detailed analysis of changes of runoff signatures by Hanus et al. (2021). In simple terms, catchments become wetter in winter (increased soil moisture, slightly more precipitation and less snow fall) and drier in summer (less precipitation and drier soils). The trigger-type resolved analysis reflects these outcomes.

Our study represents a first attempt for a regional, trigger-type resolved assessment on future debris-flow activity in the Eastern Alps. The trigger model is based on hydro-meteorological signatures of debris-flow days in the past and how often such days will occur in the future. Arguments for doing so is that (1) a trigger-type resolved susceptibility assessment outperforms rainfall-only approaches for past events (Prenner et al., 2018), and (2) we can assess seasonal and regional changes of each trigger type separately. Importantly, we do not assess changes of debris-flow event magnitude (i.e. volume), which is the most important quantity in engineering hazard assessment (Huerlimann et al., 2008). It is possible that the frequency of future convective rainfall in summer decreases while corresponding intensity increases (Pichelli et al., 2021), which potentially may lead to an increase of debris-flow volume. For the initiation of debris flows this may be of strong relevance as short-duration storms were responsible for about 2/3 of debris-flows events in the past (Prenner et al., 2019).

At annual resolution, we do not find substantial changes of the number of days susceptible for debris-flow initiation. This is similar to the expectations of future debris-flow activity in two regions in the Italian and French Alps reported by Turkington et al. (2016), who used a combination of meteorological parameters as proxies for critical debris-flow initiation conditions. On a monthly basis we find a more diverse picture. Our results indicate an extension of the debris-flows season towards late winter and even spring. This mostly supports the findings of Stoffel et al. (2014) for the western Alps who expect more debris-flow events in the shoulder-seasons (i.e. spring and fall). For the current study, we find that both, short-duration storms as well as long-lasting rain tend to become more probable earlier in the year, but the extend of this shift and related type of trigger, may, however, vary from region to region. For most regions, events triggered by long-lasting rainfall become less probable in summer. All in common is that snow-melt related trigger conditions are becoming more frequent in late winter/early spring, reflecting the general expectation of a precipitation shift from snow towards rain earlier in the year (Berghuijs et al., 2014). For recent years, we saw a statistically significant increase of rain-on-snow events in a small catchment on north-eastern Switzerland (Beniston and Stoffel, 2016) and extreme temperatures and multiple rain-on-snow events in the Alpine region even in winter (Stoffel and Corona, 2018). The expected increase of such conditions is also supported by our study; however, we cannot specify the absorbing or snow-melt accelerating effect of a rain-on-snow event for specific torrential catchments. Given the general low number of snow-melt related trigger conditions compared to rainfall-related triggers in summer, as well as that for only a few regions rainfall-related triggers will be become less probable in summer (e.g. a decreasing trend of long-lasting rainfall in the low-alpine region Paltental), we mainly expect an extension of the debris-flow season in our study regions, rather than a shift.

Debris-flow activity is not only controlled by a certain intensity or duration of rainfall, but also by hydrological and geomorphological boundary conditions that may vary over time (Bovis and Jakob, 1999). This study covers the most important aspects of the hydrological component; however, the geomorphological aspects are not included. The debris-flow catchments in our study regions may be associated with sediment-limited as well as sediment-unlimited conditions. It has been shown that increasing temperatures lead to an increase of physical weathering in high altitudes (Allen and Huggel, 2013; Bernard and Gregoretti, 2021) and that additional sediment input can lead to increased debris-flow activity (Baer et al., 2017). Stoffel and Huggel (2012) argue that drier summers will allow an increased accumulation of debris in the channel which may lead to less frequent but larger magnitudes. Yet, in catchments, where sediment-supply is driven by frost-weathering, increased future temperatures may lead to a reduction of sediment re-charge to the channel at mid-altitude ranges and by that to a reduction of debris-flow frequency, as found in the catchment-scale study of Hirschberg et al. (2020). Both effects may apply to certain parts of our study regions. Furthermore, some sub-catchments in the regions Montafon, Pitztal and Defereggental are affected by the retreat of glaciers and thawing of permafrost, where considerable amounts of debris may be released (Lugon and Stoffel, 2010). These high-elevation sites have a small extension compared to the area of the modelled regions, hence we expect a minor bias for our analysis. On the other hand, the database of past debris flows from these locations and by that our experience is limited. We cannot rule out debris-flow events of unprecedented magnitude or cascading events as recently observed in a similar alpine setting (Walter et al., 2020). An elevation-resolved quantification of the extent and temporal variation of the geomorphological disposition is not yet available even though this would be of importance for a more complete climate change impact assessment in our study regions.

6. Conclusions

In this study we connect a calibrated rainfall-runoff model (Prenner et al., 2019) with climate projections until 2100 (Switanek et al., 2022) to assess changes of hydro-meteorological trigger conditions for debris flows in six regions in the Austrian Alps. The trigger model (Prenner et al., 2018) is based on criteria sets defined for different trigger types (long-lasting rainfall LLR, short duration storm SDS, snow-melt SM and rain-on-snow RS).

The patterns of changes are regionally consistent for both emission scenarios and future periods. In other words, for each region, changes of trigger conditions are similar for the different realizations of future climate, only the magnitude of changes increases with emission scenario and further future period. A general finding is that we mostly find the highest increase of critical weather conditions early in the year (typically March and April), whereas in summer, which in the past was the typical season for debris flows, the probability of at least one trigger type decreases. Given the uncertainties stemming from the model representation and climate projections, we conclude:

- At an annual basis, there is no strong signal for changes of any trigger type in our study regions.
- We find distinct seasonal as well as regional differences of trigger conditions. SDS conditions mostly expand to spring. For the eastern regions we find a decreasing (or continuously low) frequency during summer time. Regions south of the alpine chain, especially the Gailtal, will experience SDS conditions as early as January through March.
- LLR conditions show similar patterns, i.e. a shift to periods earlier in the year, but with a general tendency of decreasing probabilities during summer. Changes in fall are more diverse, with no to slightly increased LLR frequency.
- Snow-related trigger conditions are strongly impacted by climate change. RS receives a more prolonged period than future conditions, while SM periods shorten and shift to times earlier in the year.
- From the seasonal shifts, an extension of the debris flow season from summer months into spring is expectable. Due to drier summers, it seems likely that more sediment will accumulate in or close to torrential channels, which lead to less frequent but more voluminous debris-flow events in the future. Furthermore, additional sediment sources will be available for high alpine zones of regions Montafon, Pitztal and Defereggental in the future because of glacier retreat and thawing permafrost.

CRediT authorship contribution statement

Roland Kaitna: Conceptualization, Methodology, Supervision, Project administration, Funding acquisition, Resources, Writing - Original draft and Editing. **David Prenner**: Software, Data curation, Methodology, Visualization, Software, Visualization, Investigation. **Matt Switanek:** Data curation, Methodology, Investigation. **Douglas Maraun**: Conceptualization, Supervision, Writing- Reviewing draft and Editing. **Markus Stoffel:** Conceptualization, Writing - Reviewing draft and Editing. **Markus Hrachowitz**: Conceptualization, Supervision, Methodology, Investigation, Writing - Reviewing and Editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project received financial support from the Austrian Climate and Energy Fund and was carried out within the framework of the ACRP Programme (project numbers B464795 and B960253). The computational results presented have been achieved in part using the Vienna Scientific Cluster (VSC).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162227.

References

Allen, S., Huggel, C., 2013. Extremely warm temperatures as a potential cause of recent high mountain rockfall. Glob. Planet. Chang. 107, 59–69. https://doi.org/10.1016/j.gloplacha.2013.04.007.

Allen, M.R., Ingram, W.J., 2002. Constraints on future changes in climate and the hydrologic cycle. Nature 419 (6903), 224–232. https://doi.org/10.1038/nature01092.

Baer, P., Huggel, C., McArdell, B.W., Frank, F., 2017. Changing debris flow activity after sudden sediment input: a case study from the Swiss Alps. Geol. Today 33 (6), 216–223. https://doi.org/10.1111/gto.12211.

Ballesteros-Cánovas, J., Stoffel, M., Corona, C., Schraml, K., Gobiet, A., Tani, S., et al., 2016. Debris-flow risk analysis in a managed torrent based on a stochastic life-cycle performance. Sci. Total Environ. 557, 142–153. https://doi.org/10.1016/j.scitotenv.2016.03.036.

Beniston, M., Stoffel, M., 2016. Rain-on-snow events, floods and climate change in the Alps: events may increase with warming up to 4°C and decrease thereafter. Sci. Total Environ. 571, 228–236. https://doi.org/10.1016/j.scitotenv.2016.07.146.

Bennett, G.L., Molnar, P., McArdell, B.W., Burlando, P., 2014. A probabilistic sediment cascade model of sediment transfer in the Illgraben. Water Resour. Res. 50 (2), 1225–1244. https://doi.org/10.1002/2013WR013806.

Berghuijs, W.R., Woods, R.A., Hrachowitz, M., 2014. A precipitation shift from snow towards rain leads to a decrease in streamflow. Nat. Clim. Chang. 4 (7), 583–586. https://doi.org/10.1038/nclimate2246.

Bernard, M., Gregoretti, C., 2021. The use of rain gauge measurements and radar data for the model-based prediction of runoff-generated debris-flow occurrence in early warning systems. Water Resour. Res. 57 (3), e2020WR027893. https://doi.org/10.1029/2020WR027893.

Berti, M., Martina, M., Franceschini, S., Pignone, S., Simoni, A., Pizziolo, M., 2012. Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. J. Geophys. Res. Earth Surf. 117, F04006. https://doi.org/10.1029/2012JF002367.

Berti, M., Bernard, M., Gregoretti, C., Simoni, A., 2020. Physical interpretation of rainfall thresholds for runoff-generated debris flows. J. Geophys. Res. Earth Surf. 125 (6), e2019JF005513. https://doi.org/10.1029/2019JF005513.

Beven, K., Lamb, R., 2017. The uncertainty cascade in model fusion. Geol. Soc. Lond., Spec. Publ. 408 (1), 255–266. https://doi.org/10.1144/SP408.3.

Beven, K.J., Almeida, S., Aspinall, W.P., Bates, P.D., Blazkova, S., Borgomeo, E., et al., 2018. Epistemic uncertainties and natural hazard risk assessment – part 1: a review of different natural hazard areas. Nat. Hazards Earth Syst. Sci. 18 (10), 2741–2768. https://doi.org/10.5194/nhess-18-2741-2018.

Bogaard, T., Greco, R., 2018. Invited perspectives: hydrological perspectives on precipitation intensity-duration thresholds for landslide initiation: proposing hydro-meteorological thresholds. Nat. Hazards Earth Syst. Sci. 18 (1), 31–39. https://doi.org/10.5194/nhess-18-31-2018.

Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M., 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. J. Hydrol. 518, 194–205. https://doi.org/10.1016/j.jhydrol.2014.05.022.

Bovis, M.J., Jakob, M., 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Process. Landf. 24 (11), 1039–1054. https://doi.org/10.1002/(sici)1096-9837(199910)24:11<1039::aid-esp29>3.0.co;2-u.

Broennimann, S., Rajczak, J., Fischer, E.M., Raible, C.C., Rohrer, M., Schaer, C., 2018. Changing seasonality of moderate and extreme precipitation events in the Alps. Nat. Hazards Earth Syst. Sci. 18 (7), 2047–2056. https://doi.org/10.5194/nhess-18-2047-2018.

Brunetti, M., Lentini, G., Maugeri, M., Nanni, T., Auer, I., Boehm, R., Schoener, W., 2009. Climate variability and change in the Greater Alpine Region over the last two centuries based on multi-variable analysis. Int. J. Climatol. 29 (15), 2197–2225. https://doi.org/10.1002/joc.1857.

Caine, N., 1980. The rainfall intensity: duration control of shallow landslides and debris flows. Geogr. Ann. Ser. B Phys. Geogr. 1, 23–27.

Clark, M.P., Wilby, R.L., Gutmann, E.D., Vano, J.A., Gangopadhyay, S., Wood, A.W., et al., 2016. Characterizing uncertainty of the hydrologic impacts of climate change. Curr. Clim.Chang.Rep. 2 (2), 55–64. https://doi.org/10.1007/s40641-016-0034-x.

Decaulne, A., Saemundsson, P., Petursson, O., 2005. Debris flow triggered by rapid snowmelt: a case study in the Glei. arhjalli area, northwestern Iceland. Geogr. Ann. Ser. A Phys. Geogr. 87 (4), 487–500. https://doi.org/10.1111/j.0435-3676.2005.00273.x.

Dietrich, A., Krautblatter, M., 2017. Evidence for enhanced debris-flow activity in the Northern Calcareous Alps since the 1980s (Plansee, Austria). Geomorphology 287, 144–158. https://doi.org/10.1016/j.geomorph.2016.01.013.

Doblas-Reyes, F.J., Soerensson, A.A., Almazroui, M., Dosio, A., Gutowski, W.J., Haarsma, R., Hamdi, R., Hewitson, B., Kwon, W.-T., Lamptey, B.L., Maraun, D., Stephenson, T.S., Takayabu, I., Terray, L., Turner, A., Zuo, Z., 2021. Linking global to regional climate change. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1363–1512 https://doi.org/10.1017/9781009157896.012.

Dowling, C.A., Santi, P.M., 2014. Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011. Nat. Hazards 71 (1), 203–227. https://doi.org/10.1007/s11069-013-0907-4.

Fuchs, S., Roethlisberger, V., Thaler, T., Zischg, A., Keiler, M., 2017. Natural hazard management from a coevolutionary perspective: exposure and policy response in the European Alps. Ann. Am. Assoc. Geogr. 107 (2), 382–392. https://doi.org/10.1080/24694452.2016.1235494.

Gao, H., Hrachowitz, M., Fenicia, F., Gharari, S., Savenije, H.H.G., 2014. Testing the realism of a topography-driven model (FLEX-Topo) in the nested catchments of the Upper Heihe, China. Hydrol. Earth Syst. Sci. 18 (5), 1895–1915. https://doi.org/10.5194/hess-18-1895-2014.

Gariano, S.L., Guzzetti, F., 2016. Landslides in a changing climate. Earth Sci. Rev. 162, 227–252. https://doi.org/10.1016/j.earscirev.2016.08.011.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M., 2014. 21st century climate change in the European Alps - a review. Sci. Total Environ. 493, 1138–1151. https://doi.org/10.1016/j.scitotenv.2013.07.050.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., 2008. The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5 (1), 3–17. https://doi.org/10.1007/s10346-007-0112-1.

Hanus, S., Hrachowitz, M., Zekollari, H., Schoups, G., Vizcaino, M., Kaitna, R., 2021. Future changes in annual, seasonal and monthly runoff signatures in contrasting Alpine catchments in Austria. Hydrol. Earth Syst. Sci. 25 (6), 3429–3453. https://doi.org/10.5194/hess-25-3429-2021.

Hargreaves, G.H., Samani, Z.A., 1982. Estimation of potential evapotranspiration. J. Irrig. Drain. Div.Proc. Am. Soc. Civ. Eng. 108 (IR3), 223–230.

Hausfather, Z., Peters, G.P., 2020. Emissions – the 'business as usual' story is misleading. Nature 577 (7792), 618–620. https://doi.org/10.1038/d41586-020-00177-3.

Hirschberg, J., Fatichi, S., Bennett, G.L., McArdell, B.W., Peleg, N., Lane, S.N., et al., 2020. Climate change impacts on sediment yield and debris-flow activity in an alpine catchment. J. Geophys. Res. Earth Surf. n/a (n/a), e2020JF005739. https://doi.org/10.1029/2020JF005739.

Hirschberg, J., Badoux, A., McArdell, B.W., Leonarduzzi, E., Molnar, P., 2021. Evaluating methods for debris-flow prediction based on rainfall in an Alpine catchment. Nat. Hazards Earth Syst. Sci. 21 (9), 2773–2789. https://doi.org/10.5194/nhess-21-2773-2021.

Hrachowitz, M., Weiler, M., 2011. Uncertainty of precipitation estimates caused by sparse gauging networks in a small, mountainous watershed. J. Hydrol. Eng. 16 (5), 460–471. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000331.

Huerlimann, M., Rickenmann, D., Medina, V., Bateman, A., 2008. Evaluation of approaches to calculate debris-flow parameters for hazard assessment. Eng. Geol. 102 (3), 152–163. https://doi.org/10.1016/j.enggeo.2008.03.012.

Hungr, O., Evans, S., Bovis, M., Hutchinson, J., 2001. A review of the classification of landslides of the flow type. Environ.Eng.Geosci. 7 (3), 221–238.

IPCC, 2014. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland 151 pp.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Yiou, P., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14 (2), 563–578. https://doi.org/10.1007/s10113-013-0499-2.

Jacob, D., Teichmann, C., Sobolowski, S., Katragkou, E., Anders, I., Belda, M., et al., 2020. Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community. Reg. Environ. Chang. 20 (2), 51. https://doi.org/10.1007/s10113-020-01606-9.

Jomelli, V., Brunstein, D., Grancher, D., Pech, P., 2007. Is the response of hill slope debris flows to recent climate change univocal? A case study in the Massif des Ecrins (French Alps). Clim. Chang. 85 (1), 119–137. https://doi.org/10.1007/s10584-006-9209-0.

Jomelli, V., Brunstein, D., Déqué, M., Vrac, M., Grancher, D., 2009. Impacts of future climatic change (2070–2099) on the potential occurrence of debris flows: a case study in the Massif des Ecrins (French Alps). Clim. Chang. 97 (1), 171–191. https://doi.org/10.1007/s10584-009-9616-0.

Lugon, R., Stoffel, M., 2010. Rock-glacier dynamics and magnitude–frequency relations of debris flows in a high-elevation watershed: Ritigraben,Swiss Alps. Glob. Planet. Chang. 73 (3), 202–210. https://doi.org/10.1016/j.gloplacha.2010.06.004.

Maraun, D., 2013. Bias correction, quantile mapping, and downscaling: revisiting the inflation issue. J. Clim. 26 (6), 2137–2143. https://doi.org/10.1175/JCLI-D-12-00821.1.

Maraun, D., Shepherd, T.G., Widmann, M., Zappa, G., Walton, D., Gutiérrez, J.M., et al., 2017. Towards process-informed bias correction of climate change simulations. Nat. Clim. Chang. 7 (11), 764–773. https://doi.org/10.1038/nclimate3418.

Maraun, D., Knevels, R., Mishra, A.N., Truhetz, H., Bevacqua, E., Proske, H., et al., 2022. A severe landslide event in the Alpine foreland under possible future climate and land-use changes. Commun. Earth Environ. 3 (1), 1–11. https://doi.org/10.1038/s43247-022-00408-7.

Marra, F., Destro, E., Nikolopoulos, E.I., Zoccatelli, D., Dominique, J., Creutin, F.G., Borga, M., 2017. Impact of rainfall spatial aggregation on the identification of debris flow occurrence thresholds. Hydrol. Earth Syst. Sci. Discuss. https://doi.org/10.5194/hess-21-4525-2017.

McGuire, L.A., Rengers, F.K., Kean, J.W., Staley, D.M., 2017. Debris flow initiation by runoff in a recently burned basin: is grain-by-grain sediment bulking or en-masse failure to blame? Geophys. Res. Lett. https://doi.org/10.1002/2017GL074243.

Mostbauer, K., Kaitna, R., Prenner, D., Hrachowitz, M., 2018. The temporally varying roles of rainfall, snowmelt and soil moisture for debris flow initiation in a snow-dominated system. Hydrol. Earth Syst. Sci. 22 (6), 3493–3513. https://doi.org/10.5194/hess-22-3493-2018.

Oorthuis, R., Huerlimann, M., Vaunat, J., Moya, J., Lloret, A., 2022. Monitoring the role of soil hydrologic conditions and rainfall for the triggering of torrential flows in the Rebaixader catchment (Central Pyrenees, Spain). Landslides https://doi.org/10.1007/s10346-022-01975-8.

Parajka, J., Merz, R., Bloeschl, G., 2005. Regional water balance components in Austria on a daily basis. Oesterreichische Wasser- Und Abfallwirtschaft 57 (3), 43–56. https://doi.org/10.1007/BF03165611.

Patzelt, G., 2015. The Austrian glacier inventory GI 1, 1969, in ArcGIS (shapefile) format. PANGAEA - Data Publisher for Earth & Environmental Science https://doi.org/10.1594/PANGAEA.844983.

Pichelli, E., Coppola, E., Sobolowski, S., Ban, N., Giorgi, F., Stocchi, P., et al., 2021. The first multi-model ensemble of regional climate simulations at kilometer-scale resolution part 2: historical and future simulations of precipitation. Clim. Dyn. 56 (11), 3581–3602. https://doi.org/10.1007/s00382-021-05657-4.

Prenner, D., Kaitna, R., Mostbauer, K., Hrachowitz, M., 2018. The value of using multiple hydrometeorological variables to predict temporal debris flow susceptibility in an alpine environment. Water Resour. Res. 54 (9), 6822–6843. https://doi.org/10.1029/2018WR022985.

Prenner, D., Hrachowitz, M., Kaitna, R., 2019. Trigger characteristics of torrential flows from high to low alpine regions in Austria. Sci. Total Environ. 658, 958–972. https://doi.org/10.1016/j.scitotenv.2018.12.206.

Rengers, F.K., McGuire, L.A., Kean, J.W., Staley, D.M., Hobley, D.E.J., 2016. Model simulations of flood and debris flow timing in steep catchments after wildfire. Water Resour. Res. 52 (8), 6041–6061. https://doi.org/10.1002/2015wr018176.

Rennó, C.D., Nobre, A.D., Cuartas, L.A., Soares, J.V., Hodnett, M.G., Tomasella, J., Waterloo, M.J., 2008. HAND, a new terrain descriptor using SRTM-DEM: mapping terra-firme rainforest environments in Amazonia. Remote Sens. Environ. 112 (9), 3469–3481. https://doi.org/10.1016/j.rse.2008.03.018.

Rickenmann, D., 2016. Methods for the Quantitative Assessment of Channel Processes in Torrents (Steep Streams). CRC Press, London https://doi.org/10.1201/b21306.

Rolland, C., 2003. Spatial and seasonal variations of air temperature lapse rates in Alpine regions. J. Clim. 16 (7), 1032–1046.

Schloegl, M., Fuchs, S., Scheidl, C., Heiser, M., 2021. Trends in torrential flooding in the Austrian Alps: a combination of climate change, exposure dynamics, and mitigation measures. Clim. Risk Manag. 32, 100294. https://doi.org/10.1016/j.crm.2021.100294.

Sevruk, B., 1997. Regional dependency of precipitation-altitude relationship in the Swiss alps. In: Diaz, H.F., Beniston, M., Bradley, R.S. (Eds.), Climatic Change at High Elevation Sites. Springer Netherlands, Dordrecht, pp. 123–137 https://doi.org/10.1007/978-94-015-8905-5_7.

Stoffel, M., Corona, C., 2018. Future winters glimpsed in the Alps. Nat. Geosci. 11 (7), 458–460. https://doi.org/10.1038/s41561-018-0177-6.

Stoffel, M., Huggel, C., 2012. Effects of climate change on mass movements in mountain environments. Prog. Phys. Geogr. 36 (3), 421–439. https://doi.org/10.1177/0309133312441010.

Stoffel, M., Lièvre, I., Conus, D., Grichting, M.A., Raetzo, H., Gaertner, H.W., Monbaron, M., 2005. 400 years of debris-flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland. Arct. Antarct. Alp. Res. 37 (3), 387–395. https://doi.org/10.1657/1523-0430(2005)037[0387:YODAAT]2.0.CO;2.

Stoffel, M., Tiranti, D., Huggel, C., 2014. Climate change impacts on mass movements: case studies from the European Alps. Sci. Total Environ. 493, 1255–1266. https://doi.org/10.1016/j.scitotenv.2014.02.102.

Switanek, M.B., Troch, P.A., Castro, C.L., Leuprecht, A., Chang, H.I., Mukherjee, R., Demaria, E., 2017. Scaled distribution mapping: a bias correction method that preserves raw climate model projected changes. Hydrol. Earth Syst. Sci. 21 (6), 2649–2666. https://doi.org/10.5194/hess-21-2649-2017.

Switanek, M., Maraun, D., Bevacqua, E., 2022. Stochastic downscaling of gridded precipitation to spatially coherent subgrid precipitation fields using a transformed Gaussian model. Int. J. Climatol. 42 (12), 6126–6147. https://doi.org/10.1002/joc.7581.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93 (4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Trenberth, K.E., Dai, A., Rasmussen, R.M., Parsons, D.B., 2003. The changing character of precipitation. Bull. Am. Meteorol. Soc. 84 (9), 1205–1218. https://doi.org/10.1175/BAMS-84-9-1205.

Turkington, T., Remaître, A., Ettema, J., Hussin, H., Westen, C., 2016. Assessing debris flow activity in a changing climate. Clim. Chang. 1, 1–13. https://doi.org/10.1007/s10584-016-1657-6.

Uwihirwe, J., Hrachowitz, M., Bogaard, T.A., 2020. Landslide precipitation thresholds in Rwanda. Landslides 17 (10), 2469–2481. https://doi.org/10.1007/s10346-020-01457-9.

Van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., et al., 2011. The representative concentration pathways: an overview. Clim. Chang. 109 (1), 5. https://doi.org/10.1007/s10584-011-0148-z.

Vrugt, J.A., 2016. Markov chain Monte Carlo simulation using the DREAM software package: theory, concepts, and MATLAB implementation. Environ. Model Softw. 75, 273–316. https://doi.org/10.1016/j.envsoft.2015.08.013.

Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., de Preux, A., et al., 2020. Direct observations of a three million cubic meter rock-slope collapse with almost immediate initiation of ensuing debris flows. Geomorphology 351, 106933. https://doi.org/10.1016/j.geomorph.2019.106933.

Wilcoxon, F., 1945. Individual comparisons by ranking methods. Biom. Bull. 1 (6), 80. https://doi.org/10.2307/3001968.

Wilson, R.C., Wieczorek, G.F., 1995. Rainfall thresholds for the initiation of debris flows at La Honda,California. Environ. Eng. Geosci. 1 (1), 11–27.