Publizierbarer Endbericht

gilt für Studien aus der Programmlinie Forschung

A) Projektdaten

Allgemeines zum Projekt	
Kurztitel:	Deucalion II
Langtitel:	Determination of past and future meteorological trigger conditions of torrential processes at different temporal and spatial scales
Zitiervorschlag:	Kaitna, R. Prenner, D., Braun, M., Mostbauer, K., Heiser, M., Maraun, D., Switanek, M., Stoffel, M., Ballesteros-Cannovas, J., Hrachowitz, M. (2018): Final Report of the ACRP7 project "Determination of past and future meteorological trigger conditions of torrential processes at different temporal and spatial scales", Austrian Climate and Energy Fonds.
Programm inkl. Jahr:	ACRP, 7th Call for Proposals, 2014
Dauer:	01.06.2015 bis 31.05.2018
KoordinatorIn / ProjekteinreicherIn:	Roland Kaitna, University of Natural Resources and Life Science, Vienna
Kontaktperson Name:	Roland Kaitna
Kontaktperson Adresse:	Institut für Alpine Naturgefahren, Universität für Bodenkultur Wien Peter Jordanstr. 82, 1190 Wien
Kontaktperson Telefon:	+43 1 47654 87113
Kontaktperson E-Mail:	roland.kaitna@boku.ac.at
Projekt- und KooperationspartnerIn (inkl. Bundesland):	Douglas Maraun, University of Graz, Wegener Center for Climate and Global Change, Steiermark Markus Stoffel, University of Geneva, Climatic Change and Climate Impacts (C3i), Institute for Environmental Sciences, Switzerland Markus Hrachowitz, Delft University of Technology, The Netherlands
Schlagwörter:	Wildbachgefahren, Klimawandel, Hydrologie

Allgemeines zum Projekt	
Projektgesamtkosten:	294,815€
Fördersumme:	299,884 €
Klimafonds-Nr:	B464795
Erstellt am:	27.11.2018

B) Projektübersicht

1 Kurzfassung

(max. 2 Seiten, Sprache Deutsch)
Kurze Darstellung des Projekts, Zusammenfassung der wesentlichen Projektergebnisse qualitativ und quantitativ (bei Szenarien, Kostenanalysen, volkswirtschaftlichen Studien, Potenzialstudien sind ausgewählte nummerischen Werte festzuhalten – in % sowie die Werte selbst).

Prozesse in Wildbacheinzugsgebieten, wie Hochwasser und Muren, repräsentieren eine ernstzunehmende Gefahr in alpinen Regionen. In diesem Projekt wurden die kritischen meteorologischen und hydrologischen Auslösebedingungen von Wildbachprozessen auf unterschiedlichen zeitlichen und räumlichen Skalen untersucht.

In einem ersten Schritt wurden sämtliche dokumentieren Wildbachprozesse zwischen 1901 und 2014 mit den verfügbaren Niederschlagsmessstationen in Österreich verknüpft, um die auslösenden Niederschläge abzuleiten. Weiters wurden bedingte Auslösewahrscheinlichkeiten für verschiedene Niederschlagscharakteristika errechnet.

Die hydrologischen Auslösebedingungen wurden für sechs Regionen (Montafon, Pitztal, Defreggental, Gailtal, Paltental und Feistritztal) mittels eines konzeptionellen, prozessbasierten Niederschlags-Abflussmodell simuliert und probabilistisch ausgewertet. Zur Erkennung der Auslöseverhältnisse in den simulierten hydro-meteorologischen Variablen wurden Kriterien für jeden Auslösetyp definiert, wobei zwischen langanhaltendem Niederschlag, kurzandauernden Gewittern, Schneeschmelze und Regen auf Schnee unterschieden wurde. Darauf aufbauend wurde ein hydro-meteorologisches Suszeptibilitätsmodell für die regionale Murenvorhersage entwickelt.

In weiterer Folge wurden auf Grundlage von 28 hochauflösenden regionalen Klimamodellen für zwei Emissionsszenarien Änderungen in Folge des Klimawandels abgeschätzt. Basierend auf täglichen Niederschlagsdaten ist mit einer leichten Erhöhung der generellen Wahrscheinlichkeit von Wildbachgefahren zu rechnen. Veränderte hydrologischen Einzugsgebietszustände sowie sich ändernde Auslösebedingungen wurden für die Zeiträume der nahen Zukunft (2021-2050) und der fernen Zukunft (2071-2100) abgeschätzt. Die Ergebnisse zeigen, dass die Wintermonate feuchter und die Sommermonate trockener werden. Die mittleren jährlichen kritischen Auslöseverhältnisse für Muren sinken bis zu -2,3% (etwa 14 Tage pro Jahr) im Schnitt über alle Regionen. Wichtiger ist, dass es ausgeprägte saisonale und regionale Veränderungen der Auslöseverhältnisse eines jeden Typs gibt, wodurch es in manchen Saisonen und Regionen mit einer Erhöhung der hydrologischen Disposition für Muren kommen kann.

Die Ergebnisse des Projektes sollen eine Hilfe und Entscheidungsgrundlage im Naturgefahrenmanagement in Österreich sein.

2 Executive Summary

(max. 2 Seiten, Sprache Englisch)

Torrential processes like (flash) floods and debris flows represent a severe hazard in alpine regions. In this project, we focus on the identification of critical meteorological and hydrological trigger conditions at different temporal and spatial scales.

In a first step, we connected all documented torrential events between 1901 and 2014 with rainfall data available in Austria and derived a database of triggering event rainfalls. Further, we calculated trigger probabilities for torrential processes conditional of different rainfall characteristics. Critical hydrological trigger conditions were assessed for six contrasting regions distributed in Austria (Montafon, Pitztal, Defreggental, Gailtal, Paltental und Feistritztal) based on simulation results of a conceptual rainfall-runoff model. Subsequently a set of criteria for the different variables were defined to separating between long lasting rainfall events, short-duration storms and intensive snow melt. Building on that a hydro-meteorological susceptibility model for debris flow hazard assessment was developed.

Using an ensemble of 28 down-scaled high resolution regional climate models for two emission scenarios expected changes due to changing climatic conditions were assessed. Based on projected daily rainfall data, we expect a slight increase of the general probability of torrential hazards. Changes of hydrological conditions and critical watershed states were assessed for the near future (2021-2050) and the far future (2071-2100). Results show that winter months are getting moister while summer months are becoming drier. Mean yearly trigger conditions decrease up to -2.3% (about 14 days per year) on average over all study regions. Importantly, there are distinct seasonal and regional patterns of increasing and decreasing trigger conditions for each trigger type.

The project aims to provide useful tools and decision support for policy makers and stakeholders in Austria managing alpine hazards

3 Hintergrund und Zielsetzung

(max. 2 Seiten) *Beschreibung von Ausgangslage, Aufgabenstellung und Zielsetzung.*

Debris flows represent a severe hazard in Alpine regions. Besides basic disposition (e.g. topography, geology) and variable disposition (e.g. seasonal sediment availability or hydrologic pre-conditions), the occurrence of such disasters is mainly connected to meteorological triggers, either short, intensive rainfall events or long-lasting frontal precipitation (e.g. Stoffel et al. 2011).

Over the last decades a lot of work has been done to identify triggering rainfall amounts, intensity, or intensity-duration thresholds, mostly in conjunction with shallow landslides (see review by Guzzetti et al., 2007; 2008). To overcome the uncertainties that come with deterministic thresholds, Berti et al. (2012) outlined a probabilistic approach and derived conditional probabilities for shallow landslide initiation in the northern Apennine mountains. In the recent years also remote sensing techniques like radar or satellite data have been employed to derive rainfall thresholds at high spatial and temporal resolution (e.g. Marra et al., 2014). For the Austrian Alps the only published work is the case study of Moser and Hohensinn (1983).

The Deucalion II project investigated meteorological and hydrological trigger conditions of torrential disasters on different temporal (daily, sub-daily and sub-hourly) and spatial scales (nation-wide, regional and local) and assessed potential changes of theses trigger conditions due to changing climate conditions. The basis for the analysis is a database of torrential disasters (Austrian Event Database, AED), which includes more than 4300 (dated) torrential processes like debris flows, debris floods, bedload transport, and torrential floods, over the last 100 years, which is the period where systematic rainfall data is available.

Recent improvements of our understanding of bias correction demonstrate that state-of-the-art correction methods can neither be used to downscale precipitation to sub-grid-scales nor to sub-daily variability. Whereas the former problem might be overcome by sophisticated spatial statistical models, the latter problem requires a completely different approach including process understanding about short-term precipitation events. We therefore built all climate model-based studies upon output at the daily scale only. As an additional and very timely target the development of a spatial downscaling approach emerges, that downscales from the model grid to the considered stations in a chosen region.

In the Deucalion II project research focus was given to the

- analysis of meteorological trigger conditions at different temporal and spatial scales leading to torrential disasters in the past, the
- identification of regional hydrologic disposition of two contrasting watersheds (lower Alpine region and high Alpine region) to produce torrential disasters in the headwaters
- development of bias correction and downscaling methods to generate high-resolution climate projections based on the new EURO-CORDEX data, and to the
- prediction of changes of probabilities of meteorological conditions triggering torrential disasters on a daily timescale.

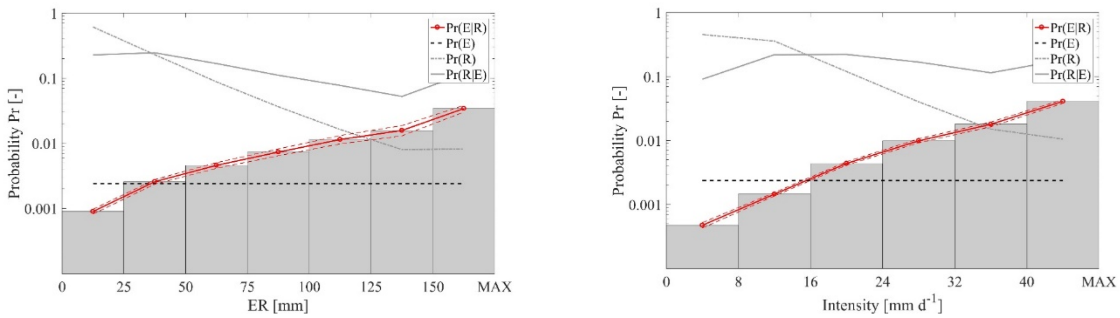
4 Projektinhalt und Ergebnis(se)

(max. 20 Seiten)

Darstellung des Projektes, der Ziele und der im Rahmen des Projektes durchgeführten Aktivitäten. Darstellung der wesentlichen Arbeitspakete und Aktivitäten. Präsentation der Projektergebnisse.

Meteorological trigger conditions (WP 1)

Trigger probabilities calculated with equ.1 (see methods section), exemplarily shown for debris flows and floods including heavy bedload transport conditional on event rainfall, are displayed in Figure 1. As expected event occurrence probability increases with increasing precipitation. We find higher probabilities for floods than for debris flows for the same amount of rainfall. Generally, with a higher event rainfall the highest probabilities are associated with rainfall intensity, the total amount of rainfall, and the 3-day antecedent rainfall.



(a) (b)

Figure 1. (a) Probability of debris flow occurrence conditional of total amount of rainfall (grey bars and red lines); (b) probability of flood including intensive bedload transport occurrence conditional of total amount of rainfall. In both plots dashed red lines refer to the 5th and 95th percentile of an assumed Poisson distributed counting error of torrential events; additionally the prior event probability $Pr(E)$ and prior rainfall probability $Pr(R)$ as well as conditional rainfall probability $Pr(R|E)$ are plotted.

The two dimensional analysis of debris flow probabilities in Austria conditional to the combination of rainfall intensity and duration shows that the highest probability emerges from high intensities > 24 mm/d (Figure 2). Interestingly we find two peaks, one at highest intensities up to 4 days and one for more moderate intensities for durations > 9 days, both cases that are relatively rare rainfall events.

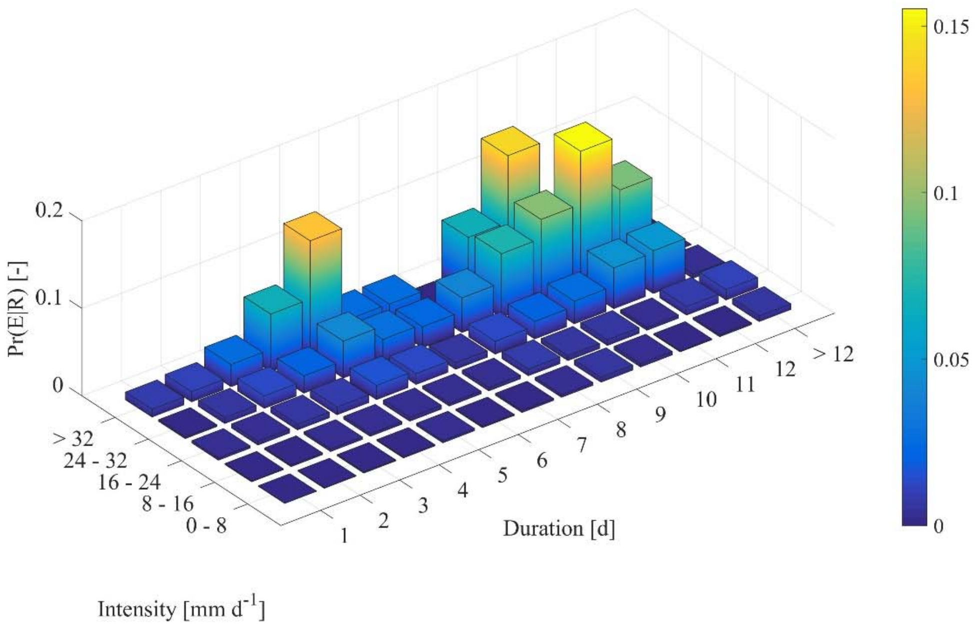


Figure 2. Probability of debris flow occurrence between 1901 and 2014 in Austria conditional to rainfall intensity and duration.

It is important to note that our analysis is biased towards long rainfall event durations. In other words, we expect that our analysis does not capture debris flow events that were triggered by short duration storms (SDS). These mostly very local convective processes typically have durations < 1-2 hours and high intensities and might not have been captured by the nation-wide rain-gauge network. As shown in WP 2 this analysis might therefore be valid only for roughly 1/3 of the debris flow occurrences in Austria.

Hydrologic disposition for triggering torrential disasters (WP 2)

Modeling performance after calibration of the six study regions reached satisfying results (e.g. Nash-Sutcliffe efficiency indexes varying between 0.7 and 0.89). Figure 3 exemplarily shows modeling results for the study region Defreggental, a high alpine valley in the southern part of the alpine chain, for the year 2012. We see highest runoff during summer and a high fraction of melt water input into the soil and channel system during spring and late fall. Soil moisture gradually builds up during spring.

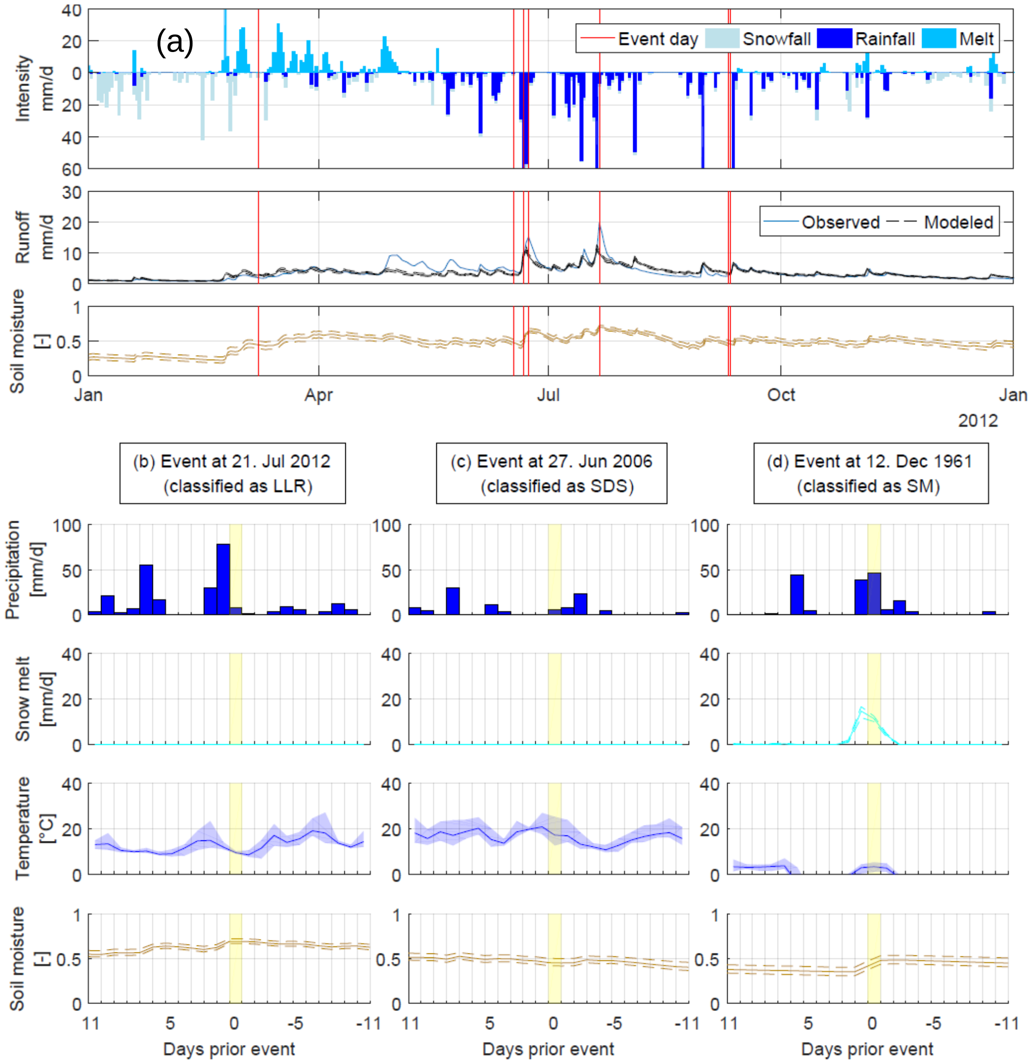


Figure 3. (a) Example of selected modeling results for the study region Defreggental for the year 2012; (b) example of a debris flow trigger that was classified as LLR, (c) as SDS, and (d) as an event were SM was important.

In the lower part of Figure 3 we show examples of the hydrologic state for three debris flow event days. In the first example there is significant rainfall prior to the event day, leading to a continuous buildup of soil moisture. At the same time temperature and especially the difference between daily minimum and maximum temperature decreases, which is typically associated with a frontal rainfall of long duration (LLR). The second example shows a contrasting picture. Though some rainfall was measured on the days prior to the event, the temperature differences are high, indicating strong solar energy input during the day. Soil moisture slightly decreases. On the event day no significant rainfall was recorded. We classified this event trigger as a convective storm event of short duration (SDS). Finally, in the third example rainfall in conjunction with intensive snowmelt (SM) triggered the debris flow event. We note that we also found debris flow event days without any recorded rainfall but very intense snowmelt. Comparing hydro-meteorological variables associated with the roughly separated trigger types (Figure 4) we find the registered event rainfall on the daily basis (which was not used for classification) is significantly higher for LLR events than for SDS events. Similarly, antecedent moisture conditions are very different, as only LLR events are connected to high soil moisture.

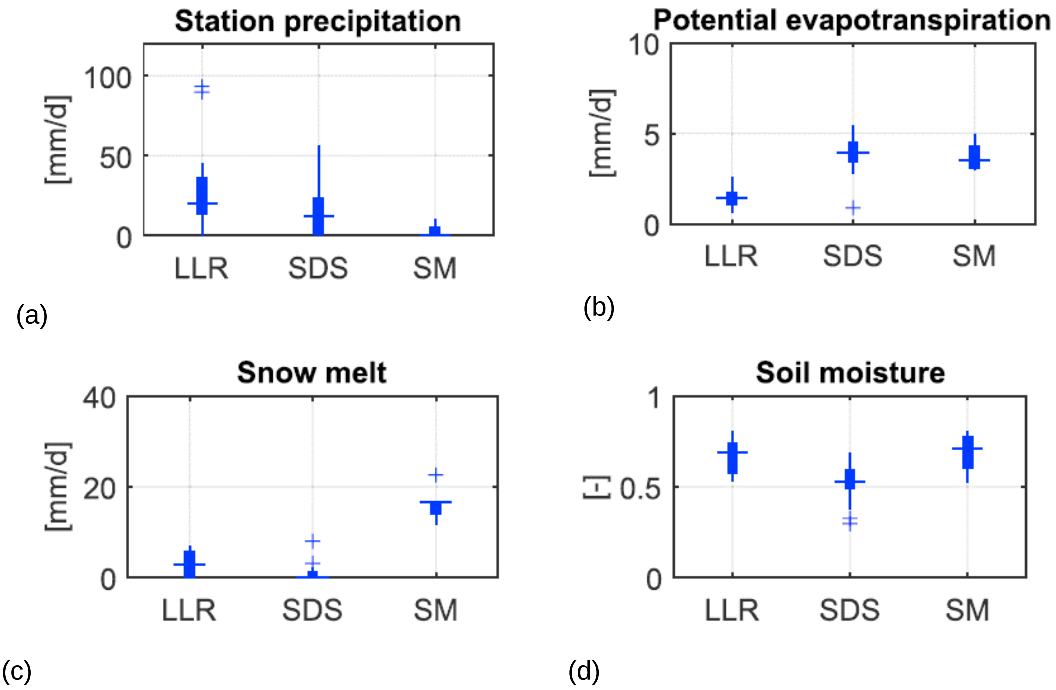


Figure 4: (a) Distribution of event day precipitation (which was not used for trigger classification), (b) potential evapotranspiration, (c) snow melt, and (d) soil moisture at event days in the Montafon region (modified after Prenner et al., 2018).

In summary we find the 50-70 % of the documented debris flows in the six study regions were triggered by SDS events, 20-44% due to LLR, and for up to 15 % snowmelt played are significant role. The investigation of the hydro-meteorological trigger conditions in six contrasting study regions indicated a strong variability of hydro-meteorological trigger conditions of documented torrential flows. The initial soil moisture as well as the rainfall on the event day, was higher for events associated with long-lasting rainfall events (LLR) than with short duration storms (SDS) across all study regions. Initial soil moisture and event day precipitation sums strongly vary across the regions for the same trigger type. Importantly, the temporal change of hydrological watershed state before events show similar signals across the regions and allows to draw more general conclusions about the susceptibility of regions to debris flow release and might allow the development of a forecasting tool as shown by Prenner et al. (2018).

Temporally and spatially resolved thresholds of precipitation triggering (WP 3)

On August 21st, 2005, an intensive rainfall event occurred in the region Montafon, triggering 57 torrential flow events. Assuming that distinct rainfall events are separated by at least one hour of no rain, the analysis of the INCA data showed that the rainfall event started at 5am and lasted for 43 hours. Figure 5(a) shows the region, the affected sub-watersheds and the grid of the INCA data. Figure 5(b) shows the density function of the 15 min rainfall (mm/15min) for all cells in the region. We find the highest densities between in the lower intensity range, a second small peak at intensities around 0.8 mm/15min and third peak at 2 mm/15min. This visualizes how un-evenly the rainfall is distributed over the region. Since we have no information on the exact timing of debris flow initiation in the sub-watersheds, we only speculate that the flows were triggered by this second and third peak.

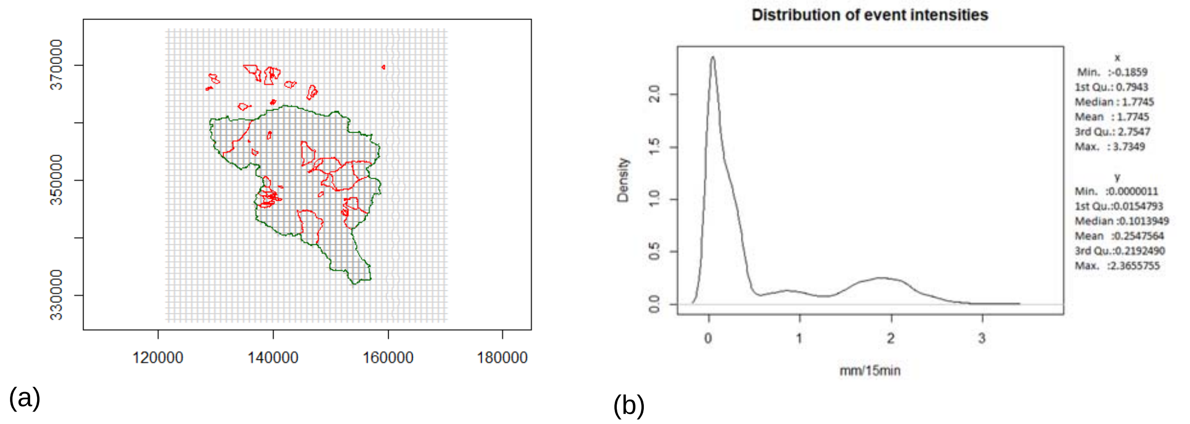


Figure 5: (a) The study region Montafon (green boundary) and sub-watersheds that were affected by the rainstorm event on August 21st, 2005 (red boundaries). The INCA grid is displayed in grey; (b) density function of the rainfall intensities in mm/15min for the rainfall event.

Development of Statistical Bias Correction and Downscaling Methods and their Application to High-resolution climate projections (WP 4)

The development of statistical bias correction and downscaling methods has substantially improved our ability to model small-scale covarying weather fields, in particular of precipitation.

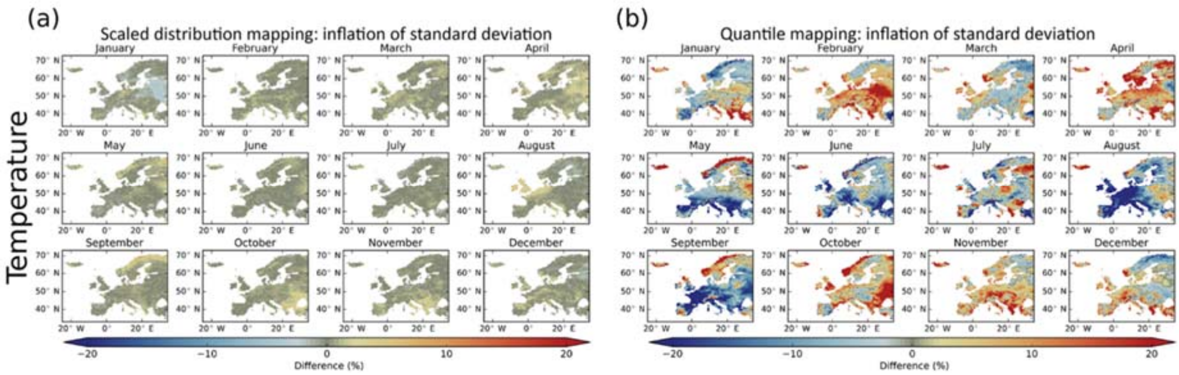


Figure 6: artificial change in the simulated trend of climate variability. (a) scaled distribution mapping, (b) conventional quantile mapping. Whereas the latter introduces strong artificial changes in climate variability, the simulated changes in climate variability are essentially preserved by the new method. This finding holds also for the mean change and changes in other statistics (not shown).

Figure 6 shows the effect of artificially changed trends in the day-to-day variability when using scaled distribution mapping (panel a) compared with standard quantile mapping (panel b). In both cases, the bias correction was calibrated on two different calibration periods (1951–1980 and 1976–2005), and the difference in the climate change signal for the period 2071-2100 was assessed. Whereas scaled distribution mapping produces almost identical changes independent of the calibration period, standard quantile mapping produces strong random trend differences, that are mostly caused by internal climate variability. The same applies for trends in means and other statistics (see Switanek et al., 2017). Thus, as long as there are no physical arguments why biases in short-term variability and long-term trends are identical (see Maraun et al. 2017 and Maraun & Widmann 2018 for discussions), scaled distribution mapping is a much more defensible choice than standard quantile mapping.

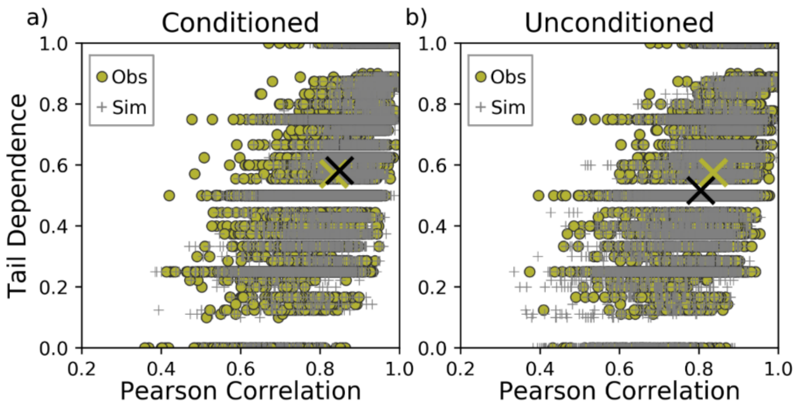
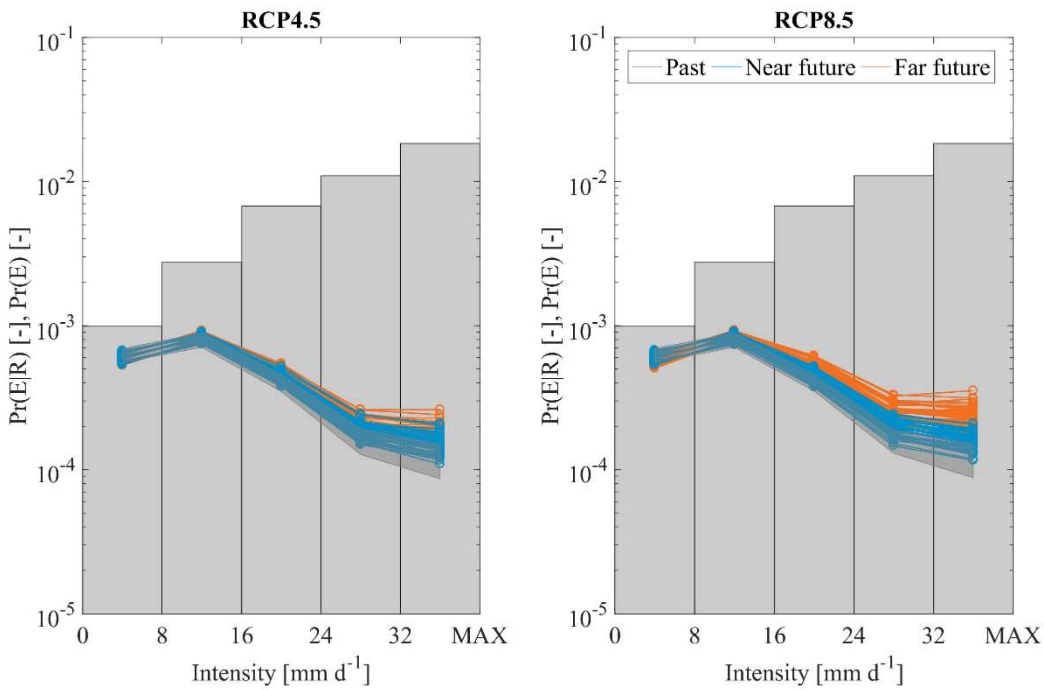


Figure 7: Capability of the transformed Gaussian model to simulate overall and extremal dependence for all station pairs. Right: without predictors correlation and tail dependence are underestimated. Left: including predictors improves the representation of dependence.

The ability of the new transformed Gaussian model to downscale precipitation has been extensively tested within the DEUCALION II project. An important assumption of this model, given by the assumption of multivariate Gaussianity of the transformed data, is that very extreme events are independent when no predictors are included. In reality, however, extreme events are correlated in space. Much of the dependence in extreme events, however, is already included in the coarse resolution predictor field (here the gridded precipitation fields). Thus, even though extremes may be conditionally (on the predictors) independent, the overall dependence including the predictor effect may still be realistic. Figure 7 confirms this reasoning. It shows both the correlation (overall dependence) and the tail dependence (for the extremes) for all considered station pairs. The right panel illustrates that a model without predictors under-represents the overall and extremal dependence. The left panel, however, shows that including predictors helps to realistically represent dependence. This example demonstrates that including physical reasoning (here in the form of predictors) may be a sensible alternative to more complex statistical models and thus may help to drastically reduce computational burden. Further tests have shown that the model produces realistic marginals and realistically extrapolates to unobserved extreme events (not shown). Scaled distribution mapping has also been applied to the ÖKS15 data set, the climate change signals of the DEUCALION II project are thus identical to the ÖKS15 signals at the RCM resolution. But additionally, the projections from the DEUCALIONII project provide a realistic sub-grid precipitation structure. Substantial further research, however, is required to understand whether the sub-grid climate change signal might be modified by local feedbacks (e.g., by latent heat realize in convective clouds). In such cases, the simulated RCM climate change signal would not be credible, and higher resolution RCMs or statistical models including the effect of these feedbacks would be required (see also Maraun et al., 2017 and Maraun and Widmann 2018).

Assessment of changes of meteorological trigger conditions and hydrologic disposition due to CC (WP 5)

As a first step we connected the outcomes of WP 1 (probabilistic TERs) with the results from WP 4 (28 climate projections). We did this for all four torrential process types and for different rainfall characteristics. Figure 8 exemplarily shows the debris flow probability with respect to total amount of rainfall separated for both emission scenarios. The grey bars represent the conditional debris flow probability of the observed past (WP 1), the grey shaded area is the debris flow probability for the past, and blue lines represent the debris flow probability for the near future (2021-2050), and the orange lines the far future (2071-2100). We see that the occurrence probability of debris flows increase mostly due to more frequent high intensity rainfalls in the future than from low intensity rainfalls. For the emission scenario RCP8.5 this increase is more pronounced.

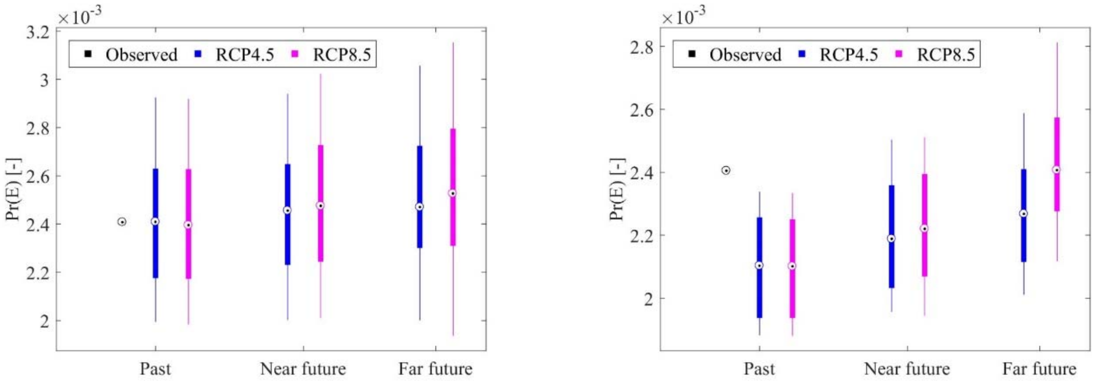


(a) (b)

Figure 8: Debris flow occurrence probability with respect to rainfall intensity for the modelled past (grey shaded area), the near future (2021-2050, blue lines), and the far future (2071-2100, orange lines), for emission scenario RCP4.5 (a) and RCP8.5 (b). Additionally the probabilities for debris flows conditional on rainfall intensity are plotted (grey bars).

Figure 9 displays the integration of debris flow occurrence probabilities with respect to rainfall intensity and total event rainfall. Additional we compare with the observed past. We find a stronger CC signal of debris flow occurrence for rainfall intensity than for total event rainfall. The latter is rather similar for both emission scenarios. Debris flow occurrence is expected to increase due to increasing rainfall intensity in the future, and especially for the far future in emission scenario RCP8.5. When comparing the debris flow occurrence probability of the observed past with the modelled past, it seems that the total rainfall can be better represented by the CC model than rainfall intensity.

The change of the hydrological trigger conditions for debris flows was assessed for all study regions (connecting WP 2 with WP 4). The modelling of all six study regions with 28 projections yielded a vast amount of data which is detailed in Prenner (2018) and Prenner et al., (in preparation). Here we show exemplarily results for the changes of future soil moisture for three study regions for both emission scenarios (Figure 10).



(a) (b)

Figure 9: Debris flow occurrence probability with respect to total event rainfall (a) and rainfall intensity (b). The RCP4.5 scenario is shown in blue and the RCP8.5 scenario in orange, separated for the near future (2021-2050) and the far future (2071-2100). Additionally the probabilities the probability for the observed past is plotted (circle with dot).

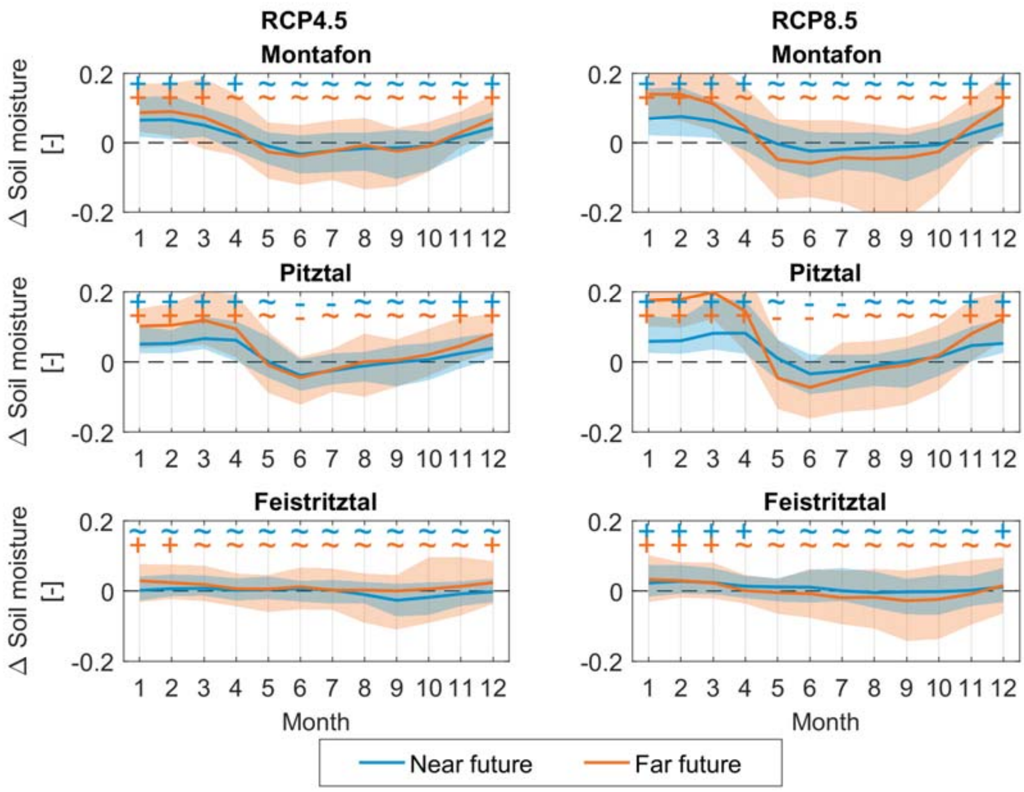


Figure 10: Example of model results of seasonal soil moisture change for the regions Montafon, Pitztal, and Feistriztal, in the near (2021-2050) and the far future (2071-2100) for both emission scenarios.

Future soils are expected to significantly be more saturated in January to March and, in the regions Montafon, Pitztal, and Paltental, also in December according to the results. This is caused by more precipitation falling as rain instead of snow as well as a quicker snow melt. During summer, there is no significant increase of soil moisture obtained at any constellation. In contrast, projected hydrological simulations suggest a significant but unclear direction of the change (Montafon and Feistritztal) or a significant decrease of soil moisture (Defereggental). In general, changes are more distinct (both, wetting and drying trends) in the far future than in the near future. Snow volumes are expected to significantly decrease in all regions, all future periods and all emission scenarios. Except for the lowest region Feistritztal, snow melt significantly increases in January and - depending on the region – in subsequent months like December, February or even months beyond that. Within the middle of spring or end of spring (April, May) snow melt rates are decreasing compared to the past. A reason for this is a higher elevated snow line in future that restricts snow melt to more elevated areas which make up only a small portion of the total precipitation zone. Future runoff changes show seasonal varying trends. In almost all regions and emission scenarios, runoff significantly increases between December and March/April. This is a result of higher snow melt rates and a higher proportion of precipitation that falls as rain. Differently, in summer time runoff trends become vague (Montafon, Feistritztal) and partly show a significant decrease (Pitztal, Defereggental, Gailtal and Paltental). Runoff changes are the smallest for the lowest region Feistritztal (reductions of 0.5 mm). However, for regions with glacier occurrence, Montafon, Pitztal and Defereggental, the uncertainty of a glacial retreat has to be considered which was neglected in the hydrological modeling.

The results show that hydro-meteorological trigger conditions will slightly decrease in the near and far future on average across all 6 study regions. However, the change of trigger conditions is quite different from one study region to the other what highlights the heterogeneity of the catchments, particularly their climatically as well as hydrologically different setting. Although the trigger frequencies decrease in all regions, the role of individual triggers are quite different.

The most distinct changes of trigger conditions were computed for the Paltental. There, the general trigger frequency decreases in the far future on median by +7% in emission scenario RCP4.5 and by +15% in RCP8.5 per year (Figure 11). Responsible for these comparatively large changes are the decrease of SDS (-10% to -21%) followed by LLR (-8% to -16%) trigger conditions. While snow melt triggered events are proposed to slightly become rare (-4% to -6%), rain-on-snow conditions are expected to increase (+2% in RCP8.5). A opposite picture is gained for the Pitztal (Figure 12). Here, conditions pointing to LLR show a clear surplus in the far future (8% RCP4.5 and 12% RCP8.5) while SM (-14% in RCP8.5) and RS (-6% in RCP8.5) conditions decrease strongest. Moderate to low changes are detected for the other regions.

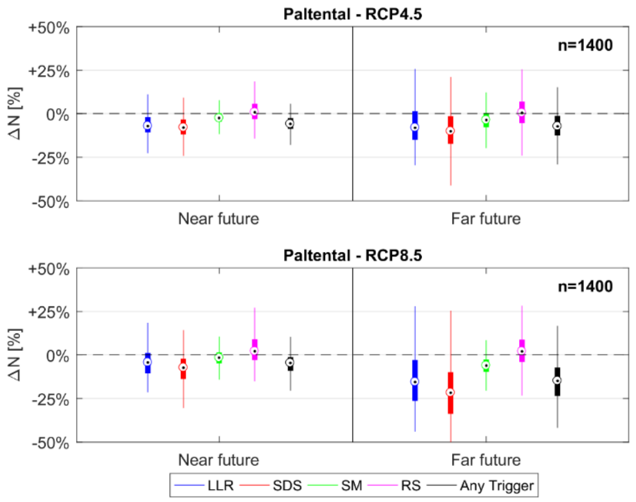


Figure 11: Yearly change of trigger conditions (LLR, SDS, SM, RS as well as without trigger differentiation) frequency in the Paltental for the near and far future period and emission scenarios RCP4.5 and RCP8.5.

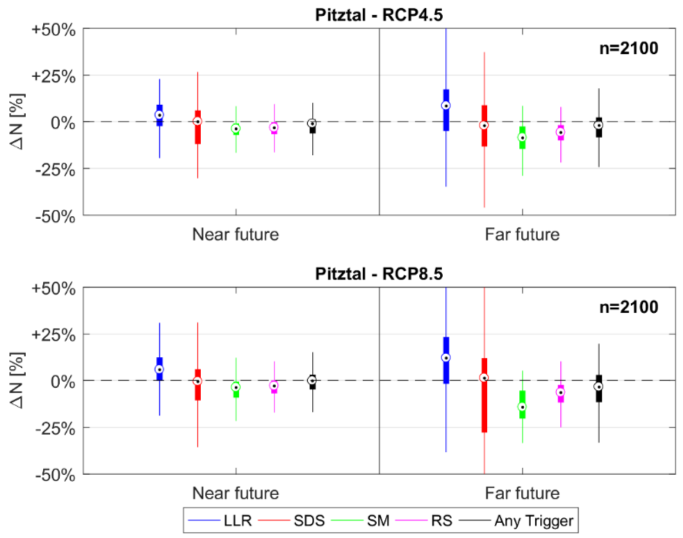


Figure 12: Yearly change of trigger conditions (LLR, SDS, SM, RS as well as without trigger differentiation) frequency in the Pitztal for the near and far future period and emission scenarios RCP4.5 and RCP8.5.

The seasonal changes of trigger conditions are evaluated on a monthly basis. Throughout all regions, results show a strong seasonality of trigger conditions. This means, that the significance of changes are different for the same trigger type across the months. Furthermore, the relative importance of a trigger type within the same months varies throughout the year. Increasing LLR trigger conditions are the most distinct in the most western regions Montafon and Pitztal for both future periods and emission scenarios from March to June and having peaks of change in April (+17% - +53%). During summer time, LLR conditions decrease across all regions (strongest in Paltental up to 34% in August in the far future of RCP8.5). In autumn, the situation is more diverse. SDS are the most frequent triggers of the past debris flows in the study regions which occurred by a large majority between June and August. Results suggest, that the period with SDS trigger conditions will be prolonged in the future. Although the highest convective potential is reached during the summer months, results show a decrease of frequency up to -32% (August in the far future of RCP8.5 in the Paltental) at the same time. This decrease tends to be larger compared to the decrease of LLR conditions. A reason for this could be the in general drier soils in the future, which are less able to satisfy the water demand requested by an enhanced evapotranspiration potential, which would be necessary to start a convective process. Increases of SDS conditions are projected for spring month April and, in the three western regions Montafon, Pitztal and Defereggental, also for May. Precipitation that fall as snow will be significantly lower in the future due to higher temperatures in our study regions. In general, rain-on-snow conditions were detected more often (on median about over six months) than increasing snow melt conditions (in about four months) throughout regions, emission scenarios, in the near and far future. In view of triggering historical debris flow events, the role of SM (including also RS) is of only minor relevance (in 4 regions only one SM triggered debris flow event occurred). An example of seasonal changing trigger conditions is exemplarily show in Figure 13 for the Montafon region.

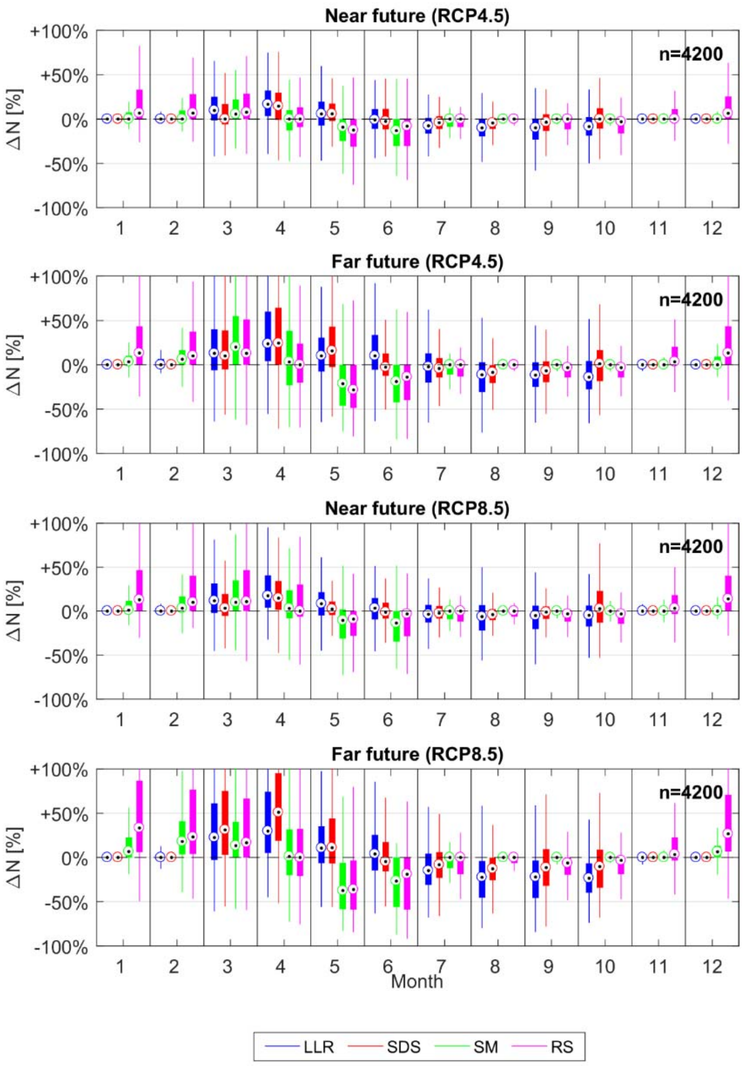


Figure 13: Seasonal change of trigger conditions (LLR, SDS, SM, RS) frequency in the Montafon for the near and far future period and emission scenarios RCP4.5 and RCP8.5.

5 Schlussfolgerungen und Empfehlungen

(max. 5 Seiten)

Beschreibung der wesentlichen Projektergebnisse. Welche Schlussfolgerungen können daraus abgeleitet werden, welche Empfehlungen können gegeben werden?

Meteorological triggers:

Data of the triggering rainfall for torrential processes are now available on a daily basis for the period 1902-2014 and on a 10-min basis for the period 1993-2014. Additionally, probabilistic thresholds were derived on a daily basis. These datasets may be used by stakeholders or the scientific community.

Connecting the probabilities of torrential events conditional on rainfall characteristics with the updated probabilities of rainfall characteristics in the future, we find a slight increase and the strongest signals for the event rainfall and rainfall intensity, especially in the higher percentile classes and for emission scenario RCP8.5. It should be noted that this analysis of based on daily rainfall data and might be therefore representative for torrential events that are not triggered by convective storm events. As the hydrological analysis showed, this might be about 1/3 of the events in the past.

Hydrological trigger conditions:

The hydrological circle of six study watersheds all over Austria was simulated by using projected climate precipitation and temperature data. To identify debris flow trigger conditions in the projected hydro-meteorological variables, criteria sets for different triggers LLR, SDS, SM and RS were defined using an exploratory approach and information from historical debris flow events in the study regions. Both, the change of trigger conditions as well as the change of hydro-meteorological catchment variables are derived by comparison of the near future period (2021 – 2050) and the far future period (2071 – 2100) with the reference period 1971 - 2000. According to this approach, following conclusions can be drawn:

- While precipitation hardly shows significant changes, temperature as well as the hydrological variables change partly significant. Potential and actual evapotranspiration increases for a large part of the year. Soils are significantly moister in winter and drier (not always significantly) in summer. Snow volumes significantly decrease and snow melt shifts towards winter months and decreases with approaching spring time. Runoff also significantly increases in winter and spring, but trends are diverse in summer. Results show that winter months are getting moister while summer months are becoming drier. Mean yearly trigger conditions decrease up to -2.3% (about 14 days per year) on average over all study regions. However, there are distinct seasonal and regional patterns of changing trigger conditions for each type. It is concluded that decreasing trigger activity will allow a higher sediment accumulation in channels in future what will lead to less frequent but more voluminous debris flows events.

- Overall average hydrological trigger conditions tend to decrease slightly in the future (up to -2.3% which equals a reduction of 14 days per year) over all regions. LLR and SDS, which triggered the majority of the historical events, show no big changes on a yearly basis. Mainly future decreases of SM and RS conditions are responsible for the overall lessening of trigger conditions. However, there are significant regional and seasonal differences. SDS conditions expand to spring months and show a decreasing frequency during summer time. LLR conditions show similar patterns but are not that distinct as SDS conditions (except for the Pitztal). RS receives a more prolonged period than future conditions of SM.
- Results show that catchment changes in scenario RCP8.5 are more distinct than in scenario RCP4.5. This trend is also observed with trigger conditions.
- From the seasonal shifts, an extension of the debris flow season from the summer months into spring and probably fall is expectable. We can speculate that additional sediment sources will be available for high alpine zones of regions Montafon, Pitztal and Defereggental in the future because of glacier retreat, thawing of permafrost soils and more intensive physical weathering at higher altitudes.

In the Deucalion II project we developed a broad understanding of meteorological and hydrological trigger conditions of torrential processes, including flash floods and debris flows. The obtained data were not yet available for Austria and the new methods may applied to other mountain regions. Algorithms and scripts, like the tool for automatic rainfall detection or automatic INCA data analysis, or the developed hydrological model (available in C as well as Matlab) will be further used in research and teaching of the project partners. (and are available for others). However, as shown by Prenner et al. (2018, in review), there is still some uncertainty in debris flow prediction even though information on hydrologic trigger conditions and the separation of trigger types strongly improves prediction performance compared to rainfall thresholds alone. This is of major relevance when predictions related to a changing climate have to be made. A future project investigating the role of geomorphologic factors limiting or favoring event initiation and especially sediment availability (storage and production) is needed. A sound understanding of the connection and interdependency between meteorology, hydrology, and geomorphology will foster forecasting tools, planning of adaption measures, and assessing the impact of climate change on the torrential processes.

C) Projektdetails

6 Methodik

(max. 10 Seiten)
Begründung und Darstellung des gewählten Forschungsansatzes.

Meteorological trigger conditions (WP 1)

This WP builds on work carried out in the first phase of "Deucalion" (ACRP 2nd call), where precipitation thresholds for three study sites in Austria (i.e. Pitztal, Lienz, Gesäuse) were estimated based on daily rainfall data. Here we applied a probabilistic approach based on Bayesian statistics and deployed this to complete Austria and differentiated between various types of torrential processes (i.e. torrential floods, debris floods, and debris flows). We applied this method to meteorological data with daily and sub-daily (10 min) resolution, which had a shorter time series and less numbers of events. The analysis based on daily rainfall data covers the period 1901 to 2014 and uses 790 time series from meteorological stations distributed over a region of approximately 80,000 km², The analysis with a 10 min resolution covers the period 1993 to 2014, with 132 time series from meteo-stations. In other words, we used meteorological data of all publicly available climate stations in Austria and connected them to our database of torrential disasters. For each observed torrential event the nearest active meteorological station was identified and the triggering event rainfall (TER) determined manually. The average distance between the location of the observed event and the next rain gauge with daily resolution was 6.1 km, and 8.6 km with sub-daily resolution.

The database of TERs are (1) a direct result available for the community, but were (2) subsequently used to calibrate a detection algorithm for automatically identifying triggering and non-triggering rainfall events in all available time series from meteo-stations. For that we used an adapted algorithm provided by Matteo Berti (personal communication) and explained in Berti et al. (2012). The probability Pr of a debris flow event E conditional of a rainfall variable R in class k=1,2,...,n was calculated with

$$Pr(E|R_k) = \frac{Pr(R_k|E) \times Pr(E)}{Pr(R_k)} \qquad (1)$$

For the import, analysis, and export of the results a set of Matlab scripts were written.

Hydrologic disposition for triggering torrential disasters (WP 2)

To get a good understanding of the probably regionally varying trigger conditions in Austria, we extended our analysis from 2 to 6 regions. We chose contrasting study regions in the Austrian Alps (Figure 14). From west to east the regions are the Montafon (west), Pitztal (west), Defereggental (south) Gailtal (south), Paltental (east) and Feistritztal (east). The regions differ according their dominant climatic influences (oceanic-west, Mediterranean-south, and continental-east), topography as well as data availability and number of observed torrential flow events.

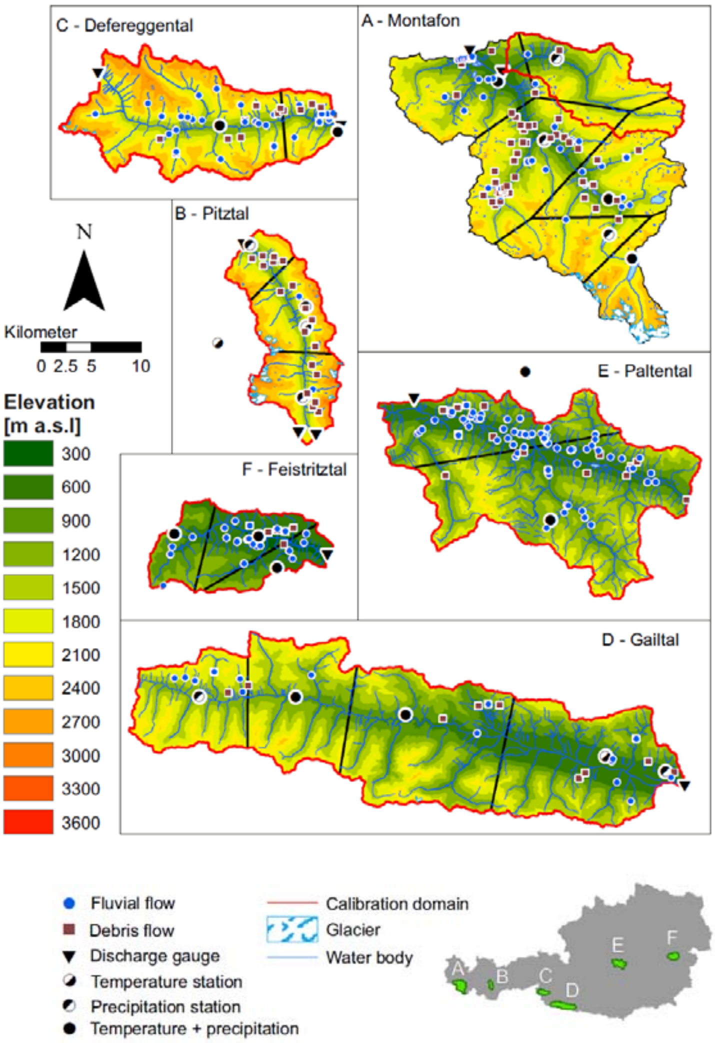


Figure 14. Overview of the six study regions Montafon (A), Pitztal (B), Defereggental (C), Gailtal (D), Paltental (E) and the Feistritztal (F) (from west to east), the location of documented torrential events (debris flows or fluvial flows), precipitation, temperature and runoff measurment stations, glaciers, water bodies and elevation distribution. Precipitation zones (based on a Thiessen polygon decomposition using the locations of available rain gauges) are marked with black-colored edges (modified after Prenner et al., in review).

The hydrological model runs of the six study regions are based on daily station data of precipitation, temperature (minimum, maximum, mean) and runoff, which are operated by the Austrian Central Institute for Meteorology and Geodynamics (ZAMG), Hydrographic Service Austria (HD) and its provincial subdivisions, hydropower plant companies Illwerke AG and Tiwag AG (see Figure 1). Further input data for the hydrological model was the CORINE Land Cover dataset from 1990, a 10x10m digital elevation model (vogis.cnv.at), a 10x10 m height-above-nearest drainage map (HAND) (Rennó et al., 2008) and a glacier distribution map (Patzelt, 2015). For each study region past torrential flow events in the sub-watersheds were available from a database provided by Hübl et al. (2008). For all sub-watersheds that experienced a documented flow event, mean aspect and Melton Ruggedness Number (elevation difference of the watershed divided by square root of the watershed area) were computed from the DEM.

A hydrological model was set up and run for each study region to obtain estimates of system state and flux variables such as soil moisture, snow melt, evapotranspiration or runoff besides the meteorological quantities of precipitation and temperature necessary for event trigger identification as well as analysis about the temporal development of watershed state before events (Figure 15). Therefore we use a semi-distributed, conceptual rainfall-runoff model, which was introduced in (Prenner et al., 2018). Since multiple rain gauges were available for every region, a Thiessen-Polygon decomposition of the study regions were used to delineate the areal influence of each station (in the following referred to as precipitation zones).

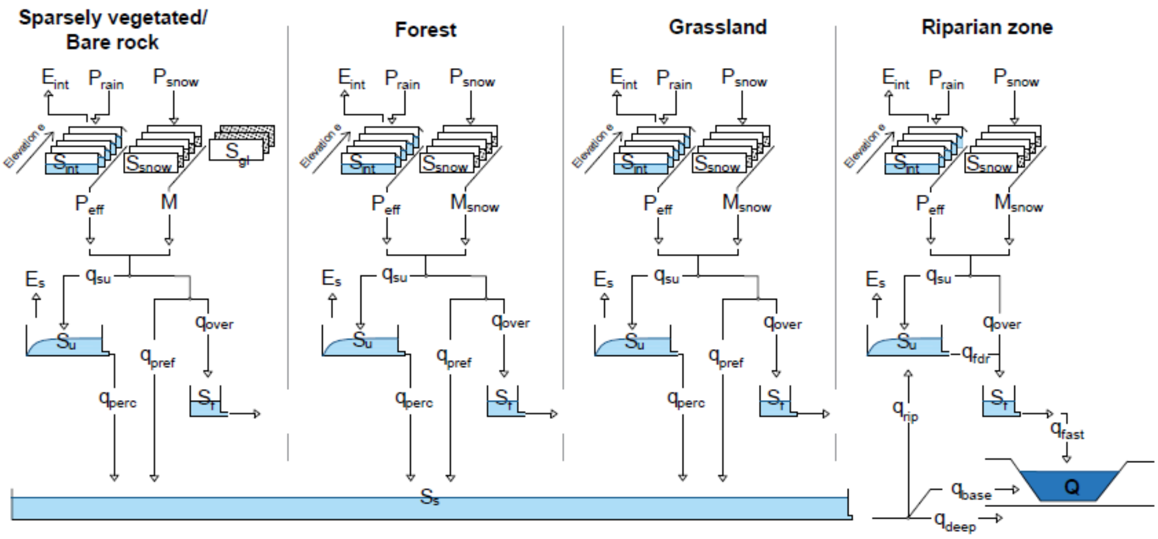


Figure 15. Structure of the hydrological model that is run for each precipitation zone (from Prenner et al., 2018).

The heterogeneous hydrological response from different land-use and topographic characteristics was considered by creating four hydrological response units (HRU) of bare rock/sparsely vegetated areas, forest, grassland and riparian zones (e.g. Gao, et al., 2014). The elevation range of each HRU was discretized into bands of 100 m to account for altitude dependent quantities like precipitation and temperature (by using altitude depended correction factors) and thereof related evapotranspiration, melt and glacier dynamics (Sevruk, 1997; Rolland, 2003). The presence of glaciers in bare rock domains are modeled as an unlimited water supply for their share they hold in an elevation zone (e.g. Gao et al., 2017). Each HRU in each precipitation zone is represented by an individual set of reservoirs for snow, glacier (active only bare rock/sparsely vegetated domain), interception, soil and fast responding surface and sub-surface. Differently, the groundwater dynamics are modeled with a single reservoir for all HRUs of a precipitation zone (Euser et al., 2015).

All computed quantities from HRUs and elevation bands are transformed by aerially weighting to the precipitation zone scale, which equals the highest resolution of available precipitation information and is therefore our working scale for the hydro-meteorological analysis. However, the modelled runoff is further upscaled from the precipitation zone scale to the watershed scale (also by area-weight) and represents the total runoff for model calibration.

For model calibration we applied the likelihood-based differential evolution adaptive metropolis sampler (DREAM) to obtain the posterior distributions of the 38 calibration parameters (Vrugt et al., 2008). Uncertainties from the hydrological modeling were considered by simulating each region with 100 different model parameter sets, randomly sampled from the parameters posterior distributions. Model performance was, post-calibration, evaluated by performance metrics Nash-Sutcliffe Efficiency of flow (NSE; Nash & Sutcliffe, 1970), NSE of the logarithm of flow (logNSE), the Volumetric Efficiency of flow (VE; Criss & Winston, 2008) as well as the NSE for the flow duration curve (FDNSE). All these measures were combined in the Euclidean distance, which states the overall model performance as degree of deviation from the optimal value of zero (e.g. Hrachowitz et al., 2014). For model warm-up we use the two years which precede the calibration period.

The identification of the trigger of the historical debris flow and fluvial flow events is based on a holistic analysis of the temporal development of watershed state before event occurrence following the approach from an exploratory study presented in Prenner et al., 2018. By this method we use multiple quantitative criteria to capture characteristic hydro-meteorological signals for the different trigger types long-lasting rainfall LLR, short duration storms SDS and intense snow melt SM. Note that avoiding, to some degree, the epistemic uncertainties from point precipitation measurements and exploiting the low-pass filter properties of watersheds (e.g. Euser et al., 2015), precipitation is here not directly used as a criterion. Instead, as demonstrated by Prenner et al. (2018), we assume that the combination of increasing soil moisture and decreasing potential evapotranspiration prior to an event-day, together with a narrow temperature span at the event day, is an indication that a LLR triggered an event. On the contrary, a decrease of soil moisture, increase of potential evapotranspiration and a large temperature span are observations typical for SDS. Finally, we interpret an intense modelled snow melt as a SM trigger. To avoid an a priori definition of so called “hard” thresholds for each criterion, threshold values were sampled a 1000 times from a uniform distribution, bounded by two plausible, representative percentiles of the value range of a hydro-meteorological variable. The trigger mechanism assigned for each torrential event was then the most frequent mechanism identified. Hydrological uncertainties are considered by alternately sampling from one of the 100 simulation runs. The determined trigger types are further cross-checked for plausibility with weather reports from the Austrian Central Institute for Meteorology and Geodynamics (ZAMG) available since 1999.

For testing statistical significance that events grouped by their trigger type (LLR, SDS or SM) or between event types (fluvial flows or debris flows) emerge from different populations, we use the Wilcoxon rank sum test (Wilcoxon, 1945). Due to limited performance of a high-end desktop PC, for modeling and calibration we employed the Vienna Scientific Cluster (VSC).

Temporally and spatially resolved thresholds of precipitation triggering (WP 3)

For the analysis of high resolution trigger conditions for recent torrential events we used the INCA dataset provided by ZAMG with a spatial resolution of 1 km² and for the period 2004 to

2014. The temporal resolution of the rainfall data is 15 minutes. Additional information like air and surface temperature, relative humidity, and radiation are available at 60 minutes time steps. We carried out the analysis not only for single events, but extended it to the study regions Montafon and Paltental for the mentioned period. Dataset contained 221 events (77 from Montafon and 144 from Paltental) represented as points with coordinates. The analysis is carried out in R and therefore the INCA data had to be automatically extracted to R. In a second step all sub-watersheds within the study region (where the events happened) had to be manually delineated as the automatic ArcGIS delineation was insufficient. For each of the watersheds mean slope, area (km2) and Melton Ruggedness number were computed. Since spatial accuracy of the INCA information is assessed with 4 km and some of the watersheds in question can be smaller than 1 km², we worked with a buffer zone of 4 km around the watershed. For the statistical analysis we use two metrics: (1) total amount of water onto the watershed (considering the buffer zone but reducing the volume to the actual watershed area) and (2) the distribution of the 15 min rainfall intensities over the whole event duration and cells (including the buffer zone).

Climate projections until 2100 (WP 4)

For the simulation of future event probabilities and hydrological catchment states, climate change projections of precipitation and temperature were needed. Some key requirements were identified for these projections: (1) they had to be provided at the station scale. (2) They should preserve the simulated climate change signal at all quantiles (including heavy precipitation). (3) They should be spatially coherent, i.e., the co-variability of meteorological variables at different stations should be realistically simulated. (4) The method for generating sub-grid fields should be computationally cheap and easy to use. No methods existed that defensibly fulfill these requirements. A key part of WP 4 was therefore the development of two novel statistical post-processing methods for climate projections that could be combined to fulfill the listed requirements. In the following, we will sketch the rationale underlying the development of these methods.

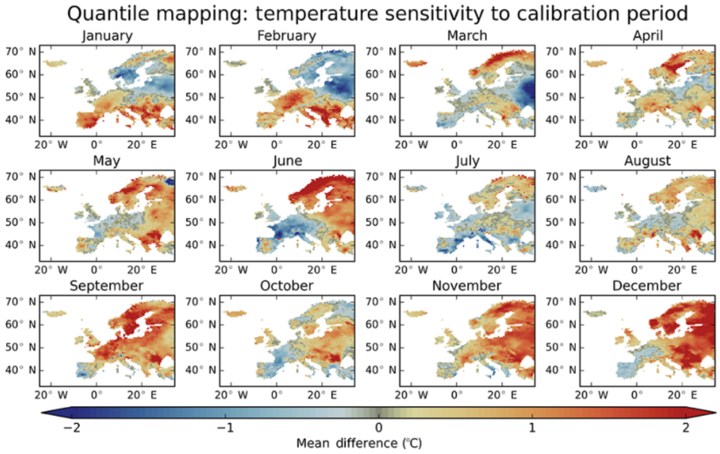


Figure 16: Mean sensitivity of simulated temperature changes (2071-2100) on the choice of the calibration period (1951-1980 and 1976-2005). Depending on the choice and region, the simulated change may change by up to 2°C just due to randomness caused by internal climate variability.

(1) Most quantile mapping methods modify the simulated climate change signal. It has been argued that these modifications are statistical artefacts and in general not physically justified (Maraun, 2013; Maraun, 2014; Switanek et al., 2017; Maraun et al., 2017; Maraun & Widmann, 2018). Switanek et al. (2017) furthermore demonstrated that these modifications are to a large extent random and may be substantially misleading (see Fig. 16), in particular for high quantiles. In a joint effort with the ACRP's CHF-FloodS project, we therefore developed a novel quantile mapping method (scaled distribution mapping, Switanek et al., 2017) that is robust against randomness and preserves the simulated climate change signal for all quantiles.

(2) Maraun (2013) demonstrated that the artificial trends discussed above are to a large extent caused by an infeasible application of quantile mapping for downscaling. These findings have been corroborated by recent research (Maraun et al., 2017, see also the detailed discussion in Maraun & Widmann, 2018). A second key aim of WP4 was therefore the development of a statistical method that can be used for downscaling precipitation fields to sub-grid (including point) scales. Such a method had been proposed already by Volosciuk et al. (2017), but this method was a single-site method only: simulated time series at two different locations were not realistically correlated. In DEUCALION II we therefore developed a novel approach based on a transformed Gaussian model that could further downscale the bias corrected precipitation fields to spatially coherent sub-grid fields (Switanek et al., 2018). They key idea of the approach is to use coarse resolution gridded precipitation fields as predictors for high-resolution (or station-based) precipitation fields. The model is calibrated on observed gridded data (here using INCA data spatially aggregated to the RCM resolution) as predictors and observed station data over the considered catchments as predictands. Several statistical models have been considered (e.g., based on pair-copula constructions, Bevaqua et al., 2017). The finally chosen model employs a transformed Gaussian distribution, because this model allows a very fast and simple implementation based on a standard Cholesky decomposition. The model works as follows:

(1) Transform observed predictor and predictand series to Gaussian marginals. Combine the transformed time series into one field, calculate the covariance matrix of this field, and the Cholesky matrix of this covariance matrix.

(2) Transform the RCM simulated predictors to Gaussian marginals. Using the Cholesky matrix, simulate random but spatially coherent predictand values conditional on the transformed predictors.

(3) Transform the simulated predictors back to the original precipitation distribution.

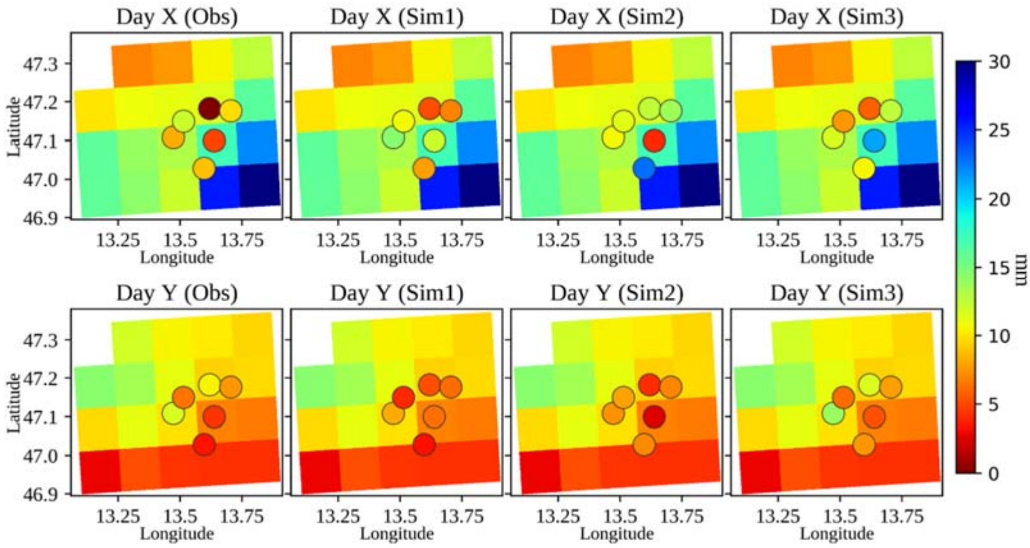


Figure 17: Stochastic downscaling of precipitation for two days (top and bottom). For each day, the coarse resolution gridded precipitation fields are identical. The left column shows the observed station data, the other columns three stochastic simulations conditional on the same gridded precipitation. The observed and simulated station data are all consistent (and equally likely) with the gridded field.

The model simulates stochastic precipitation fields similar to a conditional weather generator, i.e., ,for any given climate model simulation, a stochastic ensemble of sub-grid fields can be produced that are consistent with the coarse resolution field (see Figure 17).

Based on these methods, ensemble climate projections were generated according to the RCP4.5 and RCP8.5 radiative forcing scenarios. RCPs essentially represent different future scenarios of greenhouse gas emissions. The “moderate” scenario RCP4.5 assumes an additional forcing of 4.5 W m-2 and the “business as usual” scenario RCP8.5 an additional forcing of 8.5 W m-2 by the end of 21st century. The underlying climate model simulations were those taken from the EURO-CORDEX initiative (Jacob et al., 2014) and thus identical to the ÖKS15 ensemble. The main difference is that ÖKS15 does not realistically represent sub-grid variability. For each forcing scenario, 14 combinations of different Global and Regional Climate models (GCMs/RCMs) were used. For each climate model simulation, two stochastic sub-grid simulations were generated. So, 28 projected time series were available for each rain and temperature station in the study region and for each RCP scenario from 1970 and 2100.

Assessment of changes of meteorological trigger conditions and hydrologic disposition due to CC (WP 5)

In a first step we connected WP 1 (triggering event rainfall, TER) on a daily basis with the projections derived in WP 3 for all relevant meteorologic stations in Austria. For that we assumed that the conditional trigger probabilities derived in

WP 1 for the different rainfall metrics ($Pr(E(t=0)|R_k(t=0))$) are also valid for the future. We then calculated the probabilities for torrential event occurrence using equ. (2) for the past and compared this with the projected near future (2021-2050) and the projected far future (2071-2100).

$$\Pr(E(t)) = Pr(E(t=0)|R_k(t=0)) \times Pr(R_k(t)) \quad (2)$$

For connecting WP 2 and WP 4, the hydrological system of the six study catchments was simulated using projected climate data up to year 2100 based on two different emission scenarios RCP4.5 and RCP8.5. To identify debris flow trigger conditions based on the simulated hydro-meteorological variables (summarized in WP 2 and detailed in Prenner 2018; Prenner et al., 2018; in review), a set of criteria was defined for each trigger that is either long-lasting rainfall, short duration storm, snow melt and rain on snow. Changing catchment states as well as changing trigger conditions are outlined for periods near future (2021-2050) and far future (2071-2100) based on a probabilistic approach.

7 Arbeits- und Zeitplan

(max. 1 Seite)

Kurze Übersichtsdarstellung des Arbeits- und Zeitplans (keine Details).

DEUCALION II Project Gantt Diagram	Timescale																	
	Year 1						Year 2						Year 3					
	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26	27-28	29-30	31-32	33-34	35-36
WP 1 Long-term trigger conditions																		
M1.1 Connection of event data and meteorological date	X	X																
M1.2 Analysis of meteorological time series		X	X	X	X	X												
R1.1 Triggering rainfall on a daily basis						X	X											
R1.2 Triggering rainfall on a sub-daily basis						X	X											
WP 2 Hydrologic disposition																		
M2.1 Calibration of the hydrologic model			X	X	X	X	X	X										
M2.2 Determination of critical system parameters					X	X	X	X										
R2.1 Statistical analisis of critical system parameters							X	X	X									
R2.2 Statistical analisis of meteorological conditions								X	X	X	X	X	X					
WP 3 Highly resolved trigger conditions																		
M3.1 Analyis of highly resolved rainfall pattern for recent torrential disasters								X	X									
M3.2 Determination of geomorphic disposition of sub-catchments									X	X								
R3.1 Detailed meteorological thresholds for triggering torrential disasters										X	X	X						
R3.2 Influence of geomorphic disposition												X	X	X				
WP 4 High resolution climate projections																		
M4.1 Improved empirical-statistical bias correction					X	X	X	X	X	X	X							
R4.1 Past and future climate projections										X	X	X						
R4.2 Bias corrected precipitation and temperature scenarios for WP5												X	X	X				
WP 5 Changes of trigger conditions																		
M5.1 Analysis of model output from WP 4											X	X						
M5.2 Connection of results from WP 1 and 2 with output from WP 4												X	X	X				
R5.1 Changes of probabilities of event probabilities														X	X			
R5.2 Changes of probabilities of critical hydrologic system states														X	X	X		
WP 6 Project management, outreach and dissemination																		
M6.1 Kick-off meeting in Vienna	X																	
M6.2 Progress meetings and telephone conferences			X		X		X		X		X		X		X			X
R6.1 Climate day and international conferences				X			X			X			X			X		X
R6.2 Publications and summary for policy makers					X	X	X	X	X	X	X	X	X	X	X	X	X	X

8 Publikationen und Disseminierungsaktivitäten

Tabellarische Angabe von wissenschaftlichen Publikationen, die aus dem Projekt entstanden sind, sowie sonstiger relevanter Disseminierungsaktivitäten.

*<u>Articles (**SCI-journals)</u>*

**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 Resources Research* 54 (doi: 10.1029/2018WR022985)

**Mostbauer, K., Kaitna, R., Prenner, D., and 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, 3493-3513, (doi: 10.5194/hess-22-3493-2018)

Braun, M., Kaitna, R. (2016): Analysis of meteorological trigger conditions for debris flows on a daily time scale. In: Makarov, SA; Atutova, JV; Shekhovtsov, AI (Eds.), Debris flows: risks, forecast, protection: Materials of IV International Conference (Russia, Irkutsk – Arshan village (The Republic of Buriatia), Irkutsk: Publishing House of Sochava Institute of Geography SB RAS; ISBN: 978-5-94797-273-3.

Kaitna, R. (2016): Wildbachgefahren und Klimawandel – Das Deucalion Projekt. In *Berichte zur Klimaforschung - Naturgefahren. Austrian Climate Research Programme in Essence*. Klima- und Energiefonds, Wien.

**Ballesteros-Cánovas, J.; Stoffel, M.; Corona, C.; Schraml, K.; Gobiet, A.; Tani, S.; Sinabell, F.; Fuchs, S. & Kaitna, R. (2016): Debris-flow risk analysis in a managed torrent based on a stochastic life-cycle performance. *Science of The Total Environment* 557, 142-153 (doi: 10.1016/j.scitotenv.2016.03.036)

Ballesteros, J.A., Stoffel, M., Schraml, K., Corona, Ch., Gobiet, A., Satyanarayana, T., Fuchs, S., Sinabell, F., Kaitna, R. (in press): Understanding the impact of climate change on debris-flow risk in a managed torrent: expected future damage versus maintenance costs. *Proceedings of the 13th International Congress Interpraevent 2016*.

**Heiser, M., Scheidl, Ch., Kaitna, R. (2017): Evaluation concepts to compare observed and simulated deposition areas of mass movements. *Computational Geosciences*, pp. 1-9 (doi: 10.1007/s10596-016-9609-9).

Braun, M., Kaitna, R. (2016): Analysis of meteorological trigger conditions for debris flows on a daily time scale. In: Makarov, SA; Atutova, JV; Shekhovtsov, AI (Eds.), *Debris flows: risks, forecast, protection*: Materials of IV International conference (Russia, Irkutsk – Arshan village (The Republic of Buriatia), Irkutsk: Publishing House of Sochava Institute of Geography SB RAS; ISBN: 978-5-94797-273-3.

**Switanek, M., Troch, P., Castro, C., Leuprecht, A., Chang, H-I., Mukherjee, R., Demaria, E. (2017): Scaled distribution mapping: a bias correction method that preserves raw climate model projected changes. *Hydrology and Earth System Sciences*, 21, 2649-2666 (doi:10.5194/hess-21-2649-2017).

In review / in preparation:

**Prenner, D., Hrachowitz, M., Kaitna, R. (in review): Trigger characteristics of torrential flows from high to low alpine regions in Austria. Submitted to *Science of the Total Environment*. (accepted with minor revision)

Kaitna, R., Prenner, D., Huebl, J. (in review): Muren. In "Extremereignissen alpiner Naturgefahren (ExtremA)". Sachstandsbericht im Auftrag des Bundesministeriums für Nachhaltigkeit und Tourismus (BMNT), Abt. III/5 - Wildbach- und Lawinenverbauung.

Kaitna, R., Prenner, D., Braun, M., Hrachowitz, M. (in review): Hydro-meteorological trigger conditions of debris flows in Austria. Submitted to the 7th International Conference on Debris-Flow Hazards Mitigation.

**Kaitna, R., Braun, M., Prenner, D., Maraun, D., Switanek, M., Stoffel, M., van Nooyen, R., Hrachowitz, M. (in preparation): Debris flow triggering rainfall in the Austrian Alps: past and future development. To be submitted to *Climate Change*.

**Prenner, D., Hrachowitz, M., Maraun, D., Switanek, M., Kaitna, R. (in preparation): The influence of climate change on debris flow trigger conditions from a hydro-meteorological perspective. To be submitted to *Earth's Future*.

**Switanek, M., Maraun, D., Bevacqua, E. (in preparation): Stochastic downscaling of gridded precipitation to spatially coherent sub-grid precipitation fields using a transformed Gaussian model. To be submitted to J. Geophys. Res.

Conference contributions

Braun, M; Kaitna, R. (2018): A comparative analysis of meteorological trigger conditions for torrential processes on a daily and sub-daily time scale for Austria In: European Geosciences Union (Ed.), Geophysical Research Abstracts Vol. 20, EGU2018-16169; ISBN: 1607-7962.

Braun, M; Maraun, D; Switanek, M; Prenner, D; Kaitna, R. (2018): Analysis of past and future meteorological trigger probabilities for torrential processes in Austria using regional climate projections from the EURO-CORDEX initiative In: European Geosciences Union (Ed.), Geophysical Research Abstracts Vol. 20, EGU2018-16434; ISBN: 1607-7962.

Kaitna, R; Ballesteros, J; Braun, M; Hrachowitz, M; Maraun, D; Mostbauer, K; Prenner, D; Stoffel, M; Switanek, M. (2018): Hydro-meteorological trigger conditons of torrential hazards in the Austrian Alps In: Climate Change Centre Austria (Hrsg.), 19. Klimatag, Tagungsband, Aktuelle Klimaforschung in Österreich.

Mostbauer, K; Kaitna, R; Prenner, D; Hrachowitz, M. (2018): The temporally varying roles of rainfall, snowmelt and soil moisture for debris flow initiation in an alpine region In: EGU General Assembly 2018 (Eds.), Geophysical Research Abstracts, Vol. 20, EGU2018-4999, 2018.

Prenner, D; Kaitna, R; Mostbauer, K; Hrachowitz, M . (2018): What can hydro-meteorological variables tell us about debris flow occurrence? In: EGU General Assembly 2018 (Eds.), Geophysical Research Abstracts, Vol. 20, EGU2018-8269, 2018.

Prenner, D., Kaitna, R., Mostbauer, K., Hrachowitz, M. (2017): Hydrological disposition of flash flood and debris flows events in an Alpine watershed in Austria. Geophysical Research Abstracts Vol. 19, EGU2017- 12984, EGU General Assembly 2017.

Mostbauer, K., Hrachowitz, M., Prenner, D., Kaitna, R. (2017): Hydrologic system state at debris flow initiation in the Pitztal catchment, Austria. Geophysical Research Abstracts Vol. 19, EGU2017- 13109, EGU General Assembly 2017.

Kaitna, R., Braun, M. (2016): Meteorological trigger conditions for different geomorphic processes in steep mountain channels in the Austrian Alps. Annual Meeting of the American Geophysical Union, Abstract EP33D-1008, 12.-16.12.2016, San Francisco, USA (Poster).

Prenner, D., Kaitna, R., Hrachowitz, M. (2016): Hydrological modeling of an Alpine watershed for the identification of trigger conditions leading to flash floods and debris flows. Annual Meeting of the American Geophysical Union, Abstract NH43C-1878, 12.-16.12.2016, San Francisco, USA (Poster).

Kaitna, R., Stoffel, M., Corona, C., Truhetz, H., Maraun, D., Gobiet, A., Hrachowitz, M. (2016): Meteorological and hydrological triggers of torrential disasters in Austria in times of climate change. Proceedings of the 13th International Congress Interpraevent 2016, extended abstracts, pp. 70-71.

Braun, M., Kaitna, R. (2016): Analysis of meteorological trigger conditions for torrential processes on a daily time scale. *Geophysical Research Abstracts* Vol. 18, EGU2016-15498. EGU General Assembly 2016

Heiser, M., Scheidl, Ch., Kaitna, R. (2017): Evaluation concepts to compare observed and simulated deposition areas of mass movements. Geophysical Research Abstracts Vol. 19, EGU2017-7093, EGU General Assembly 2017.

Prenner, D., Kaitna, R., Mostbauer, K., Hrachowitz, M. (2017): Hydrological disposition of flash flood and debris flows events in an Alpine watershed in Austria. Geophysical Research Abstracts Vol. 19, EGU2017- 12984, EGU General Assembly 2017.

Mostbauer, K., Hrachowitz, M., Prenner, D., Kaitna, R. (2017): Hydrologic system state at debris flow initiation in the Pitztal catchment, Austria. Geophysical Research Abstracts Vol. 19, EGU2017- 13109, EGU General Assembly 2017.

Matthew Switanek M., Troch, P., Castro, C., Leuprecht, A., Chang, H., Mukherjee, R., Demaria, E., Maraun, D. (2017): Scaled distribution mapping: a bias correction method that preserves raw climate model projected changes. Geophysical Research Abstracts Vol. 19, EGU2017-13181

unentgeltliche, nicht exklusive, zeitlich und örtlich unbeschränkte sowie unwiderrufliche Recht einräumen zu können, das Bildmaterial auf jede bekannte und zukünftig bekanntwerdende Verwertungsart zu nutzen. Für den Fall einer Inanspruchnahme des Klima- und Energiefonds durch Dritte, die die Rechtinhaberschaft am Bildmaterial behaupten, verpflichtet sich die Fördernehmerin / der Fördernehmer den Klima- und Energiefonds vollumfänglich schad- und klaglos zu halten.

Additional references used:

Berti, M., Martina, M., Franceschini, S., Pignone, S., Simoni, A., & Pizziolo, M. (2012). Probabilistic rainfall thresholds for landslide occurrence using a Bayesian approach. Journal of Geophysical Research: Earth Surface, 117, F04006. https://doi.org/10.1029/2012JF002367.

Bevacqua E., Maraun, D. Hobaeck Haff, I., Widmann, M., and Vrac, M. (2017). Multivariate statistical modelling of compound events via pair-copula constructions: analysis of floods in Ravenna (Italy), Hydrology and Earth System Sciences, 21, 2701–2723, 2017.

Criss, R. E., & Winston, W. E. (2008). Do Nash values have value? Discussion and alternate proposals. Hydrological Processes, 22(14), 2723–2725. https://doi.org/10.1002/hyp.7072

Euser, T., Hrachowitz, M., Winsemius, H. C., & Savenije, H. H. G. (2015). The effect of forcing and landscape distribution on performance and consistency of model structures.:. Hydrological Processes, 29(17), 3727–3743. https://doi.org/10.1002/hyp.10445.

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. Hydrology and Earth System Sciences, 18(5), 1895–1915. https://doi.org/10.5194/hess-18-1895-2014.

Gao, H., Ding, Y., Zhao, Q., Hrachowitz, M., & Savenije, H. H. (2017). The importance of aspect for modelling the hydrological response in a glacier catchment in Central Asia. Hydrological Processes, 31(16), 2842-2859.

Guzzetti, F., Peruccacci, S., Rossi, M., & Stark, C. P. (2007). Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorology and Atmospheric Physics, 98(3–4), 239–267. https://doi.org/10.1007/s00703-007-0262-7.

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.

Hübl, J., Totschnig, R., & Scheidl, C. (2008a). Historische Ereignisse Band 1: Auswertung von Wildbach Schadereignissen bis 1891 auf Basis der „Brixner Chronik“ (IAN REPORT No. 111). Wien: Institut für Alpine Naturgefahren.

Hrachowitz, M., Fovet, O., Ruiz, L., Euser, T., Gharari, S., Nijzink, R., … Gascuel-Odoux, C. (2014). Process consistency in models: The importance of system signatures, expert knowledge, and process complexity. Water Resources Research, 50(9), 7445–7469. https://doi.org/10.1002/2014WR015484

Jacob, D., et al. "EURO-CORDEX: new high-resolution climate change projections for European impact research." Regional Environmental Change 14.2 (2014): 563-578.

Maraun, D. (2013). Bias Correction, Quantile Mapping and Downscaling. Revisiting the Inflation Issue. Journal of Climate 26:2137-2143.

Maraun, D. (2014). Reply to comment on "Bias Correction, Quantile Mapping and Downscaling. Revisiting the Inflation Issue". Journal of Climate 27:1821-1825.

Maraun, D., Shepherd, T.G., Widmann, M., Zappa, G., Walton, D., Gutierrez, J.M., Hagemann, S., Richter, I., Soares, P.M.M., Hall, A. and Mearns, L.O. (2017). Perspective: Towards process informed bias correction of climate change simulations, Nature Climate Change 7, 764-773.

Maraun, D. and Widmann, M. (2018). Statistical Downscaling and Bias Correction for Climate Research, Cambridge University Press.

Marra, F., Nikolopoulos, E. I., Creutin, J. D., & Borga, M. (2014). Radar rainfall estimation for the identification of debris-flow occurrence thresholds. Journal of Hydrology, 519, 1607–1619. https://doi.org/10.1016/j.jhydrol.2014.09.039

Moser, M., & Hohensinn, F. (1983). Geotechnical aspects of soil slips in Alpine regions. Engineering Geology, 19(3), 185–211.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. Journal of Hydrology, 10(3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

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.

Prenner, D. (2018): The influence of climate change on debris flow trigger conditions from a hydro-meteorological perspective. Master thesis submitted at the University of Natural Resources and Life Sciences, Vienna.

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

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 Sensing of Environment, 112(9), 3469–3481. https://doi.org/10.1016/j.rse.2008.03.018.

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

Stoffel, M., Bollschweiler, M., & Beniston, M. (2011). Rainfall characteristics for periglacial debris flows in the Swiss Alps: past incidences–potential future evolutions. Climatic Change, 105(1–2), 263–280. https://doi.org/10.1007/s10584-011-0036-6.

Volosciuk, C., Maraun, D., Vrac, M., and Widmann, M. (2017). A combined statistical bias correction and stochastic downscaling method for precipitation, Hydrology and Earth System Sciences, 21, 1693-1719.

Vrugt, J. A., ter Braak, C. J. F., Clark, M. P., Hyman, J. M., & Robinson, B. A. (2008). Treatment of input uncertainty in hydrologic modeling: Doing hydrology backward with Markov chain Monte Carlo simulation. Water Resources Research, 44(12), n/a-n/a. https://doi.org/10.1029/2007WR006720

Wilcoxon, F. (1945). Individual Comparisons by Ranking Methods. Biometrics Bulletin, 1(6), 80. https://doi.org/10.2307/3001968