Climate Change Impact on Landslide Risk – Estimating Change in Heavy Precipitation Event Frequencies

Auswirkung des Klimawandels auf das Hangrutschungsrisiko – Abschätzung des Auftretens künftiger Starkregenereignisse

Wolfgang Loibl, Mario Köstl, Johann Züger, Philip Leopold
AIT – Austrian Institute of Technology · wolfgang.loibl@ait.ac.at

Abstract**:** *Landslides can pose a serious threat to settlements and infrastructure. In addition to orographic, geologic, soil- and land-based triggers, extreme precipitation is a climate-induced trigger that can affect the strength and frequency of landslide events. Here we investigate current and future extreme precipitation events in two study areas in Austria; in Waidhofen an der Ybbs north; and in Paldau south of the Alpine main ridge; to detect possible changes in landslide risk due to climate change. The comparison of the number of extreme precipitation events in recent decades and the number of potential events in the decades to come, extracted from future climate scenarios, shows a moderate to significant increase in the number of extreme rainfall events in both study regions.*

Keywords: Landslide risk, extreme precipitation events, future climate, regional climate simulations

Zusammenfassung: *Hangrutschungen können eine ernsthafte Gefahr für Siedlungen und Infrastruktur darstellen. Neben orographischen, geologischen, boden- und landnutzungsbedingten Auslösern ist extremer Niederschlag ein klimabedingter Auslöser, der die Stärke und Häufigkeit von Hangrutschungsereignissen beeinflussen kann. Hier untersuchen wir aktuelle und potenzielle zukünftige extreme Niederschlagsereignisse in zwei Untersuchungsgebieten in Österreich: in Waidhofen an der Ybbs nördlich -, und in Paldau südlich des Alpenhauptkamms, um mögliche Veränderungen des Hangrutschungsrisikos aufgrund des Klimawandels zu identifizieren. Der Vergleich der Zahl extremer Niederschlagsereignisse der letzten Jahrzehnte mit der Zahl potenzieller Ereignisse künftiger Jahrzehnte die aus Klimaszenarien extrahiert wurden, zeigt einen moderaten bis deutlichen Anstieg der Zahl der Extremereignisse in beiden Untersuchungsgebieten.*

Schlüsselwörter: *Hangrutschungsrisiko, extreme Niederschlagsereignisse, künftiges Klima, regionale Klimasimulationen*

1 Background and Objectives

Climate change suggests an increase in future extreme events that require sustainable risk management and appropriate regulations in spatial planning to prevent or at least mitigate future dangers. Hazard prevention requires exploration of spatio-temporal dependencies between landslide occurrence and physical and climate conditions as well as their change, to identify the triggers for landslide occurrence and allocation. The study described here is part of the project "Integrating Land use Legacies in Landslide Risk Assessment to support Spatial Planning" (ILLAS, https://illassite.wordpress.com/). ILLAS aims to integrate historic land-use data, climate history and future climate simulations into landslide risk assessment. The paper focuses on climate issues of future landslide risk, assuming, that land use and geophysical properties have local impact, while climate has a large-scale impact on landslide risk. Thus, this study has two objectives:

AGIT – Journal für Angewandte Geoinformatik, 5-2019, S. 368-382. © Wichmann Verlag, VDE VERLAG GMBH · Berlin · Offenbach. ISBN 978-3-87907-669-7, ISSN 2364-9283, eISSN 2509-713X, doi:10.14627/537669035.

(1) Examining the relationship between extreme precipitation events and landslide occurrence in the study regions to confirm causal relationships.
(2) Estimating extreme precipitation events under current and future climate, quantifying the change in landslide risks.

2 Data and Methods

2.1 Study regions

Rainfall volume and heavy precipitation in particular – is highly dependent on terrain characteristics and large-scale weather effects. Figure 1 shows the location of the two study regions in Austria located north and south of the Alpine main ridge.

For the analysis of historic weather and climate conditions weather stations are selected from the project "Historical Instrumental Climatological Surface Time Series Of The Greater Alpine Region", (HISTALP, http://www.zamg.ac.at/histalp/) (Böhm, 2009), obtaining data from monitoring sites which are located close to the study regions. All HISTALP data are "homogenised" recordings, i. e. data from stations, that have been moved during the recording period, have been statistically adjusted to avoid interruption of the recordings (cf. Auer et al., 2015). Daily or monthly HISTALP data are available for around 65 Austrian weather stations with recordings starting in different years in the 19th to 20th century and end around 2008 or earlier, depending on the monitoring stations. Those HISTALP stations, which correspond with the location characteristics of the study regions, are selected to examine frequency, duration and magnitude of extreme precipitation patterns. The precipitation recordings are examined to identify periods in which extreme precipitation event occurrences coincide with landslide occurrences. For identified landslide events, the associated nearby precipitation events, are extracted.

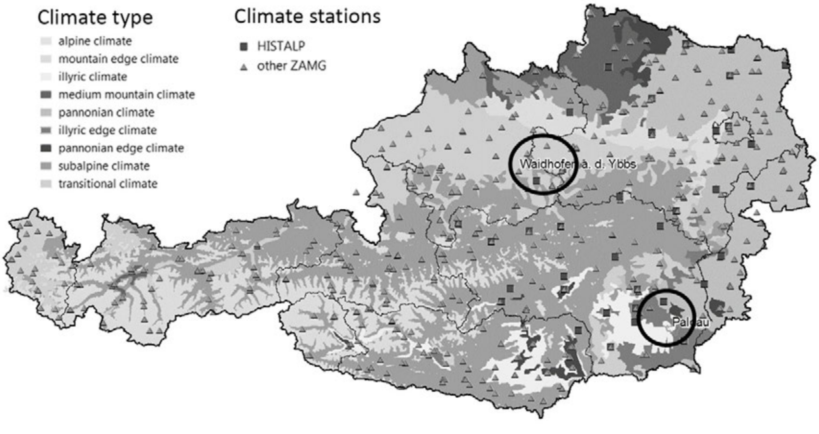


Fig. 1: Positions of the study regions Paldau (southern circle) and Waidhofen an der Ybbs (northern circle), climate type pattern and distribution of HISTALP and further ZAMG weather stations (Sources: Map: Hitz et al. (2004) – adapted, weather stations: www.zamg.ac.at/histalp)

For both study regions time series of HISTALP weather stations are selected, which correspond best to the location characteristics of the study regions. For the study region Paldau (left map in Figure 2) this is the weather station Bad Gleichenberg, 12 km to Paldau, with monthly and daily precipitation records starting from 1879. The second closest station in Graz, 30 km away, shows different climate characteristics. In the study region Waidhofen, a HISTALP weather station is located, which is recording since 1894, but only monthly data. The best match of the Bad Gleichenberg station with a station providing daily data shows the weather station Großraming in 20 km distance, with records from 1952 to 2000. The comparison of monthly precipitation totals from Waidhofen and Großraming shows a rather strong relationship, which allows to use the daily data from Großraming for further analysis of extreme events and landslide risk. HISTALP recordings are extended with data from nearby precipitation monitoring stations from "Hydrographischer Dienst", Austria's hydrological monitoring office where daily precipitation data are available for relevant years, (starting from 1970, 1980 or 2000 till 2016, depending on the station (BMNT 2015, BMNT 2019) – later called "HD monitoring data".

In terms of local climate effects, the position within the continental "mountain system" and the terrain – slope directions and the elevation – have significant implications. Figure 2 shows the terrain characteristics in both study regions with the municipality borders and the nearby weather stations selected for the precipitation analysis.

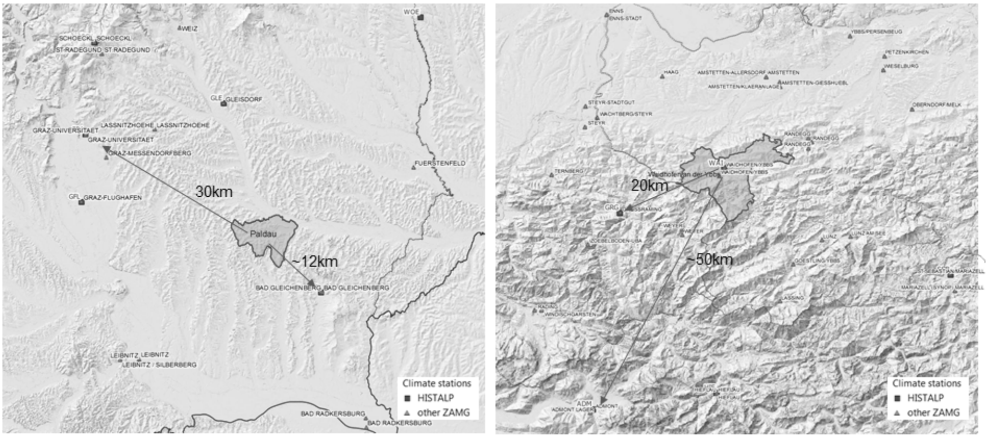
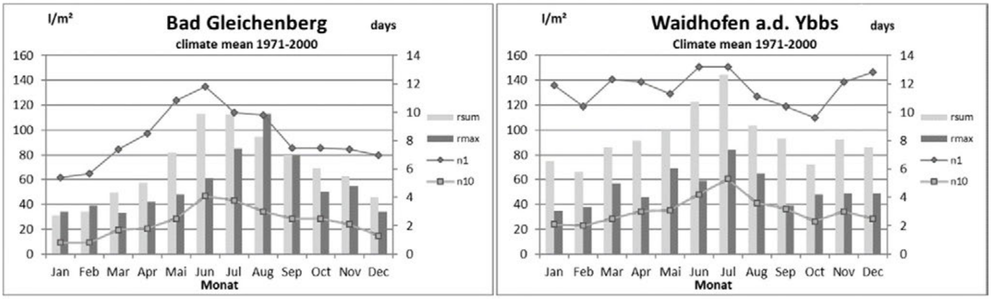


Fig. 2: Nearby HISTALP weather stations for analysing long term precipitation and temperature records for Paldau (left) and Waidhofen (right); (Source: Digital Elevation Model: www.basemap.at)

It is obvious, that both study regions differ considerably in elevation characteristics as well as in their position relative to the Alpine main ridge as a continental divide. In the study region Paldau, the maximum elevation difference is around 200 m, while in the study region Waidhofen the difference is up to 1230 m. In terms of large-scale weather effects, Paldau is shielded from Atlantic weather patterns by the Alpine main ridge. Paldau is characterized by Illyrian weather, where frontal weather patterns significantly affect the study region, moving from the southwestern Mediterranean Sea towards the Alpine main ridge causing heavy rainfall along the southern slopes. High temperatures (and humidity) in the valleys lead to convective dynamics resulting in local thunderstorms, which occur in all areas but show higher frequencies in the south. The study region Waidhofen is part of the northern Kalkalpen (Limestone Alps), at the northern edge of the Alpine main ridge, turning out as barrier for frontal weather patterns. By moving from north-western Europe and the Atlantic Ocean, they bring increased humidity resulting in frequent and rather heavy rainfalls along the slopes facing north and northwest (cf. Pfahl, 2014).

2.2 Rainfall characteristics

Figure 3 compares the long-term weather rainfall characteristics in the two study regions. The HISTALP station Bad Gleichenberg (elevation 303 m) shows a typical Mediterranean/continental-influenced annual rainfall distribution with an explicit summer maximum, mainly caused by convective precipitation, where maxima for 24 hours reach up to 130 mm. Because of the small elevation range of 200 m between valleys and hill peaks, the influence of terrain on rainfall characteristics is small.



	rsum	rmax	n1	n10
BGL	831,4	113	98,8	26,9
WAI	1133,6	84	140,4	36,8

token	unit	element	definition
rsum	l/m²	total rainfall	mean monthly sum of precipitation
rmax	l/m²	highest daily precipitation	Highest rainfall in 24 hours
n1	days	precipitation ≥ 1 mm	number of days with total precipitation ≥ 1 mm
n10	days	precipitation ≥ 10 mm	number of days with total precipitation ≥ 10 mm

Fig. 3: Comparison of precipitation distribution recorded at weather stations, which are representative for the study regions Paldau (HISTALP station Bad Gleichenberg) and Waidhofen (HISTALP station Waidhofen)

The HISTALP station Waidhofen (elevation 365 m) is located in a predominantly Atlantic influenced climate zone with annual rainfall totals of 800 – 1000 mm. Because of its position at the edge of the northern Lime stone Alps the area is affected by the so-called "Nordstaulagen" (northern orographic uplift) phenomenon: Atmosphere dynamics triggered by northwestern fronts, bring relatively constant precipitation during the year with frequent and sometimes persistent precipitation events with considerable rainfall (cf. Pfahl, 2014). Highest daily precipitation totals occur usually during the summer months, mainly because of thunderstorms: Precipitation maxima reach monthly totals of 80 mm in May and up to 120 mm in June and July. There do not exist daily data for all stations, so we look for coincidence between close stations where at least one station shows daily data among those with only monthly data. High monthly precipitation totals indicate to some extent the occurrence of heavy precipitation events during these months.

2.3 Heavy precipitation and landslide risk

To relate precipitation records to landslide risk, an indicator must be defined, which describes heavy rainfall as landslide trigger and can be derived from monitoring data as well as from climate simulation results. Heavy rainfall has many definitions across regions, as it is regionally dependent and strongly correlates with relief and soil permeability. Thus, to transfer the approach to other study areas, may require different thresholds. For our study regions, the "Moser-threshold" (Moser & Hohensinn, 1983) with an exceedance of a 40 mm daily precipitation total turns out as a good criterion for local landslide risk: For four recorded landslides in the study regions, two each in Paldau and Waidhofen, a correspondence of landslide occurrences and heavy precipitation events are identified.

2.3.1 Paldau

In the study region Paldau, two recent landslides are recorded, thus enabling the utilization of the Moser & Hohensinn, 1983 method: 2009-06-24 and 2014-09-24. Knowing the landslide occurrence days, allows to identify daily rainfall events which released landslides. Figure 4 depicts days with precipitation totals > 40 mm, linked to landslide occurrences (marked by light grey bars). The June 2009 landslide event is observed to be released by heavy rainfalls recorded in June 23rd and 24th. The September 2014 landslide is observed to be released by rainfall recorded in September 12th. (Rainfall during some previous days might also have contributed to landslide release, but with less influence).

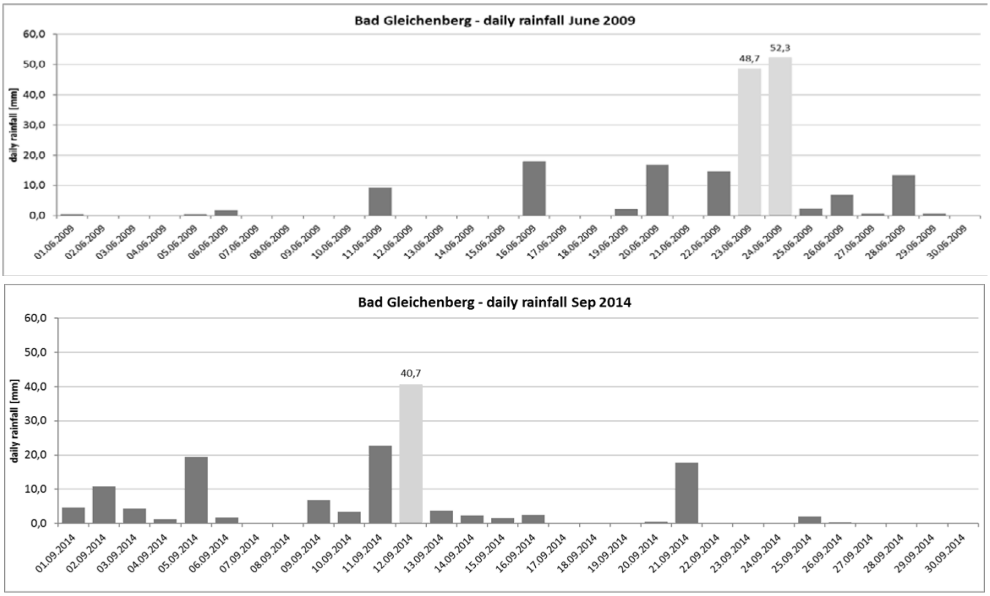


Fig. 4: Daily rainfall during June 2009 and September 2014 in Bad Gleichenberg (near Paldau): Light-grey bars mark good coincidence of heavy precipitation events with landslide occurrence (Source: ZAMG, HISTALP, extended after 2009 with neighbouring HD station recordings)

2.3.2 Waidhofen

Near Waidhofen a.d. Ybbs two recent landslides are recorded: 2002-08-11/13 and 2014-05-15/17. As the weather station Waidhofen is lacking daily monitoring data, the nearby station Großraming is selected for daily data analysis as the monthly rainfall totals from Waidhofen and Großraming stations show a rather high coincidence. Figure 5 shows the identified days with precipitation > 40 mm linked to these landslide occurrences (marked by light-grey bars).

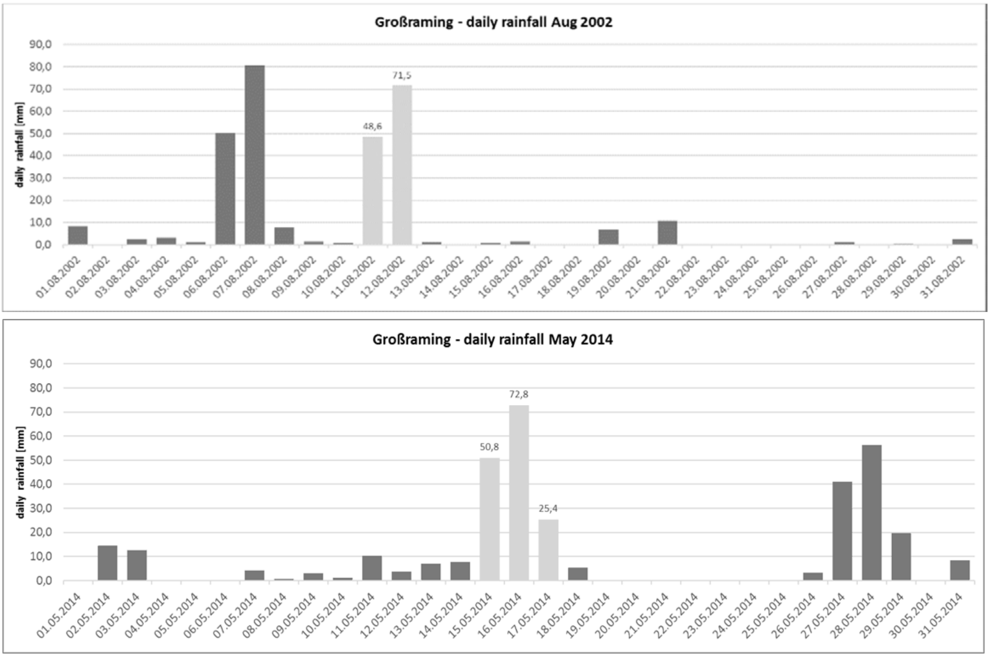


Fig. 5: Daily rainfall during August 2002 and May 2014 in Großraming (near Waidhofen): Light-grey bars mark good coincidence of heavy precipitation events with landslide occurrence (Source: ZAMG, HISTALP, extended after 2009 with neighbouring HD station recordings)

The relation of precipitation totals > 40 mm/day on landslide occurrences is confirmed by Figures 4 and 5, thus, this 40 mm/day precipitation exceedances are selected as triggers for increasing landslide risk, to be extracted from the regional climate simulations.

3 Results

3.1 Regional climate simulation and extreme event occurrence identification

Future heavy precipitation events and their intensity (and the resulting landslides) cannot be exactly “predicted”. But transient climate simulations allow for the identification of daily rainfall totals from hourly simulation results, enabling the estimation of the frequency and magnitude of heavy precipitation events indicated by these daily sums.

Regional Climate Models (RCMs), conduct spatio-temporal simulations of the atmospheric physics considering the interaction of the atmosphere with surface, land cover, cryosphere and hydrosphere. The models thus also consider gas concentrations in the atmosphere – e. g. CO2, Methane and further – which increases the greenhouse effect, the ability to capture energy emitted by Earth's surface. RCMs use 6-hourly results from global climate simulations as forcing data, carried out by GCMs – General Circulation Models. Regional Climate Simulations are repeated, stepwise applying smaller model domains – from continental extent to alpine ridge extent, to Austrian country extent – with steadily improved spatial resolution from 250 and more km to 100×100 km, 30×30 km, 10×10 km, 4×4 km to 1×1 km grid spacing.

For our future climate extreme event assessment, the COSMO-CML-based simulation results, carried out within the reclip:century project are used (Loibl W. et al., 2013). (COSMO stands for consortium for small scale modelling, www.cosmo-model.org) COSMO-CML is a regional climate model, based on the operational non-hydrostatic mesoscale weather forecast model, initially developed by the German Weather Service (DWD) and later by the European COSMO Consortium (Rockel, et al., 2008). Applying regional climate models, we have conducted hindcast simulation runs, using gridded global observation data (ERA40) as model forcing. We further conducted control simulation runs using GCM simulations under on current GHG concentration as forcing data and scenario simulation runs using GCM results assuming future GHG increase as forcing data. The global control and scenario runs were obtained from the GCM of the UK "Met Office Hadley Centre for Climate Science and Services" HADCM3. The applied greenhouse gas (GHG) scenario was A1B, assuming moderate greenhouse gas increase, derived by the 4th Assessment Report (AR4) of the intergovernmental Panel on Climate Change (IPCC, 2007), similar to the RPC4,5 and RPC6,0 scenario assumptions (Representative Concentration Pathways) as projected in the 5th IPCC Assessment Report (IPCC, 2014) (AR5) for the period 2021-2050.

The "Klimaszenarien für Österreich" (ÖKS15) – datasets (CCCA, 2019), which are based on the more recent AR5 scenarios, cannot be used here for extreme event extraction, as this requires daily simulation results to find relationships between extreme precipitation and landslide occurrence, which are not available.

Therefore, selected daily results are made available from the reclip: century – simulations with 10×10 km, 4×4 km and 1×1 km grid spacing. The finally applied 1×1 km grid spacing is sufficient for our purpose: Very local precipitation events below 1 km resolution may not occur in the 1×1 km grid spacing results, but they did not occur in the precipitation observations and recent climate simulations either. Here the change of the climate framework conditions is compared, triggering land slide risk in a general way. Local land slide risk is expected to be far more affected by slope angle, geology, soil and land cover, than by local precipitation variation (cf. Reichenbach et al., 2013).

3.2 Paldau climate simulation results exploration

3.2.1 Uncertainty assessment

First, we check, if and how simulation results match observations. Therefore, a simple uncertainty assessment is conducted by comparing a control simulation run, reflecting current GHG conditions, with the hindcast simulation run, applying ERA40 data from the European

Centre for Medium-Range Weather Forecasts (ECMWF), which are re-analysed and homogenised worldwide observation data, gridded with 125 km resolution (https://www.dkrz.de/up/services/data-management/projects-and-cooperations/era40-1).

A detailed uncertainty assessment, conducted by comparing various RCM simulation results with forcing data from different GCMs using different GHG scenarios, would require far more resources than available for this project task.

The uncertainty range describes the accuracy of the model output. The smaller the deviations, the smaller is the uncertainty. Figure 6 shows the long-term frequency of days > 40 mm rainfall, extracted from the COSMO-CML hindcast run with ERA40 forcing and the corresponding COSMO-CML control run under current GHG conditions. The results are extracted for the study region Paldau, using the spatial maximum of all 1×1 km cells. The figure shows the number of extreme events per year as bar chart (10-year moving averages) and a 3-period moving average as line chart. In the upper left corner, 30-year extreme precipitation event frequencies from the control – and the hindcast runs are shown. (Frequencies are calculated for the decadal periods 1961-1990, 1971-2000, 1981-2010 and the most recent 10-year period 1986-2015 as current reference period) to show the steady change during prior decades. In the upper right corner, the differences of the modelled extreme event occurrences between the control – and the hindcast run 1986-2015 are depicted.

In general, the COSMO-CML/HADCM3 simulation results show a higher number of heavy precipitation days above 40 mm/d, than the COSMO-CML/ERA40 simulation results. The depicted differences of the 30-year periods turn out smaller when related to single years. The 30-year event differences in the spatial mean between both simulation runs are between –2 and +5 days over each 30-year period, which ranges between –0,07 to +0,17 events per year, and can be judged as an extreme low uncertainty over the 30-year periods, unless during single years higher uncertainty ranges occur.

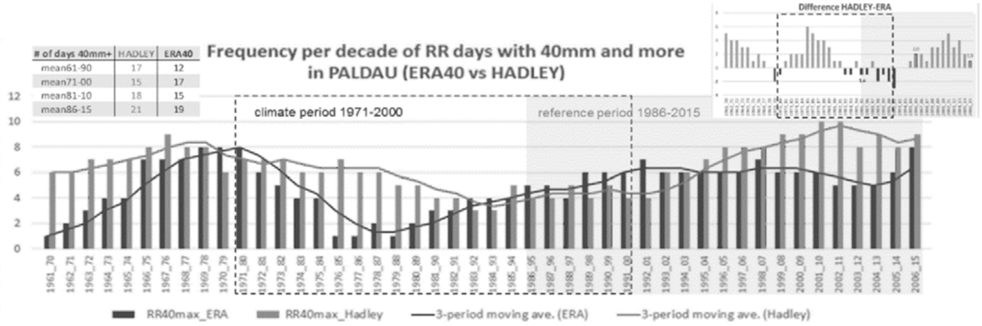


Fig. 6: Decadal frequency of days with precipitation > 40 mm/d between 1961 and 2015 based on the spatial MAX of all cells in study region Paldau (Source: analysis of reclip:century simulations: COSMO-CML/ERA40 run and COSMO-CML/HADCM3 control run)

Figure 7 shows the spatial distribution of the COSMO CML/ERA40 hindcast, the COSMO-CML/HADCM3 control run results and the relative differences between both simulations for the reference period 1986-2015. The differences in the spatial variation are quite low, again indicating high coincidence and thus low uncertainty. The heavy precipitation day variation of the hindcast run differs between 0.47 and 0.63 extreme events per year. The control run shows a slightly higher frequency than the hindcast run (0.6 to 0.7 against 0.5 to 0.6 extreme events per year). The centre of the case study region, the uncertainty is between 10 to 15 %. The overall spatial mean of the hindcast run is 0.57 compared to 0.65 extreme event days of the control run. The overall relative difference is just 14 %, which is a very good level of agreement.

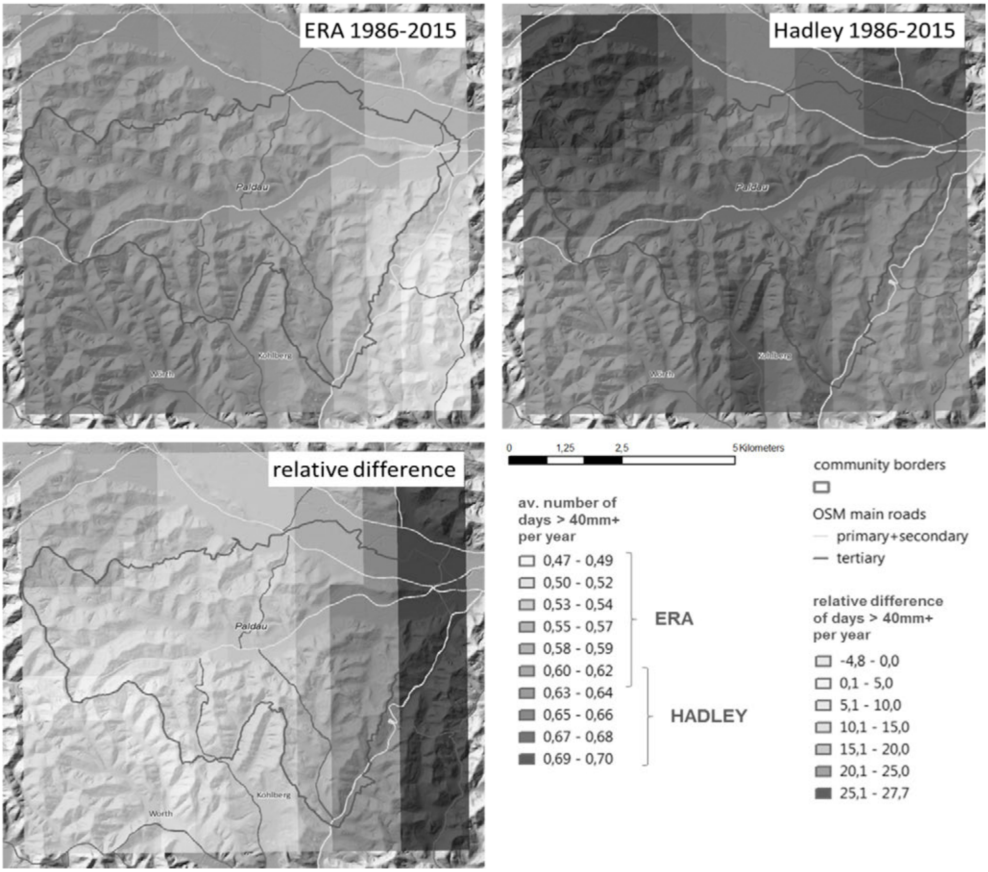
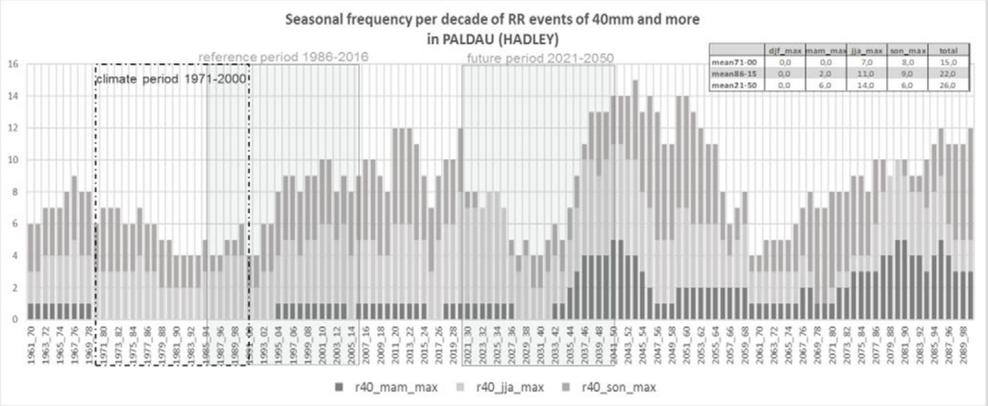


Fig. 7: Uncertainty assessment 1986-2015 for the study region Paldau: Days with precipitation > 40 mm/day per year (10-year averages) from the COSMO-CML/ERA40 hindcast run 1986-2015 (top left), from the COSMO-CML/HADCM3 control run 1986-2015 (top right) (30-year averages) and the relative difference of hindcast – control run 1986-2015 (bottom left). (Source: analysis of reclip:century simulations)

3.2.2 Future extreme precipitation events and landslide risk

In Figure 8 the average number of days with precipitation > 40 mm/d for Paldau, from the COSMO-CML/HADCM3 A1B scenario run, divided into seasons, is presented for the climate standard period 1971-2000 and the future period 2021-2050 as 10-year moving averages. As both figures show the averaged decadal frequencies until the end of the 21st century, the (most likely NAO-driven) long-term oscillation is visible. The NAO – the North Atlantic Oscillation – refers to fluctuations in the difference of sea level pressure (SLP) between the Icelandic Low atmospheric pressure and the Azores High atmospheric pressure and its changes over time with varying periodicity. SLP differences let indicate speed and volume of westerly winds across the North Atlantic, bringing more or fever storms and rainfall to Europe (cf. National Weather Service-Climate Prediction Center, 2019).



	djf_max	mam_max	jja_max	son_max	total
mean71-00	0,0	0,0	7,0	8,0	15,0
mean86-15	0,0	2,0	11,0	9,0	22,0
mean21-50	0,0	6,0	14,0	6,0	26,0

Fig. 8: Expected seasonal frequency (per decade) of days with precipitation > 40 mm/d 1961-1970 to 2091-2100 in Paldau from COSMO-CML/HADCM3 A1B scenario simulation; the reference and future periods considered in the study are marked. (Source: analysis of reclip:century simulations)

By comparing the two periods 1986-2015 and 2021-2050, two similar aspects can be observed: (1) both periods show a precipitation increase in their second half of the decade, and (2) the future period has, according to the NAO influence, a significant depression in the late 2020s and early 2030s, resulting in a reduction of heavy rainfall days during all seasons. However, looking at a 30-year period, the changes are not so extreme, as shown in the top right table in Fig. 8. The number of heavy rainfall days rises from 15 days in the climate period 1971-2000 to 22 days in the reference period 1986-2015, up to 26 days in the future climate period 2021-2050. Concerning seasonal deviations, the future autumn seasons show less heavy precipitation days as those in the reference period 1971-2000.

In Figure 9 the mapping results for the study region, from the COSMO-CML/A1B scena-rio run for the future period 2020-2051 are compared with the COSMO-CML current climate control run 1986-2015: The average number of heavy rainfall days rises from 0.6 – 0.7 up to 0.73 – 0.97 extreme events per year. The relative changes range from 4 % in the north-west to 62 % in the south-west. In the east, an increase of 24 – 45 % can be expected. The spatial mean of all cells rises from 0.65 to 0.86 events per year, comprising as an average relative change of 33 % in the centre.

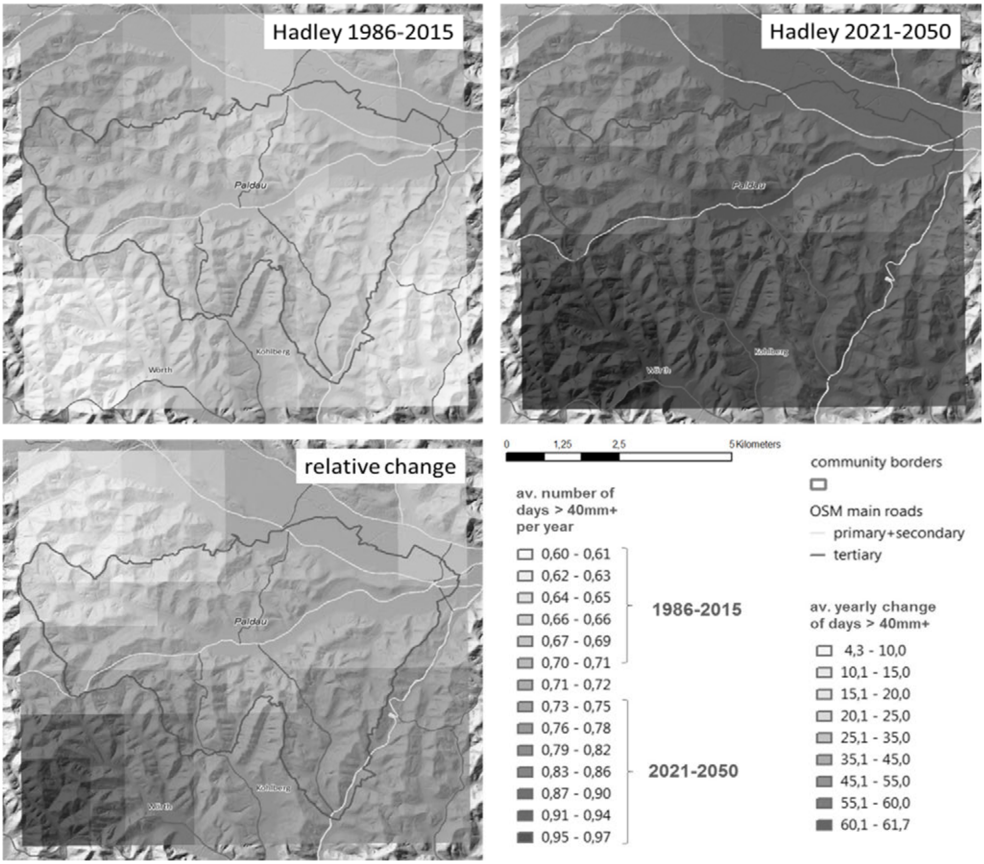


Fig. 9: Expected climate change signals for study region Paldau: Days with precipitation > 40 mm/day per year (30-year average) from COSMO-CML/HADCM3 control run 1986-2015 (top left), COSMO-CML/HADCM3 A1B scenario run 2021-2050 (top right), and relative change between future and reference period (bottom left) (Source: analysis of reclip:century simulations.)

3.3 Waidhofen climate simulation results exploration

3.3.1 Uncertainty assessment

For Waidhofen the same uncertainty assessment and the long-time extraction of heavy rainfall days from the scenario simulation until 2100 is carried out. Fig 10 depicts the low uncertainty range: The spatial mean of the hindcast run is 1.48 extreme event days per year compared to 1.5 extreme event days from the control run, leading to a negligible overall relative difference of 2 %.

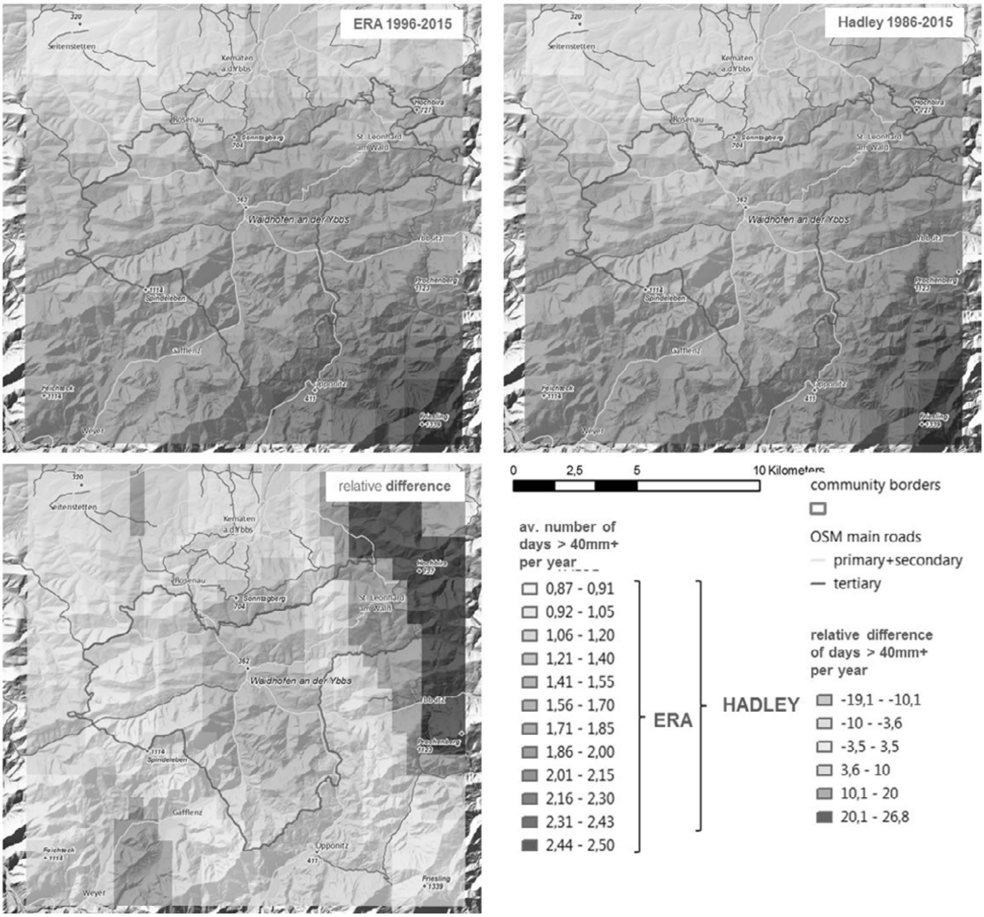


Fig. 10: Uncertainty assessment 1986-2015 for the study region Waidhofen: Days with precipitation > 40 mm/day per year (30-year averages) from the COSMO-CML/ERA40 hindcast run 1986-2015 (top left), from the COSMO-CML/HADCM3 control run 1986-2015 (top right) (30-year averages) and the relative difference of hindcast – control run 1986-2015 (bottom left). (Source: analysis of reclip:century simulations)

3.2.2 Future extreme precipitation events and landslide risk

The impact of the NAO phenomenon on the large scale temporal precipitation pattern, to be expected for Waidhofen, is similar as for Paldau, so Figure 8 can serve here also as a reference for Waidhofen.

In Figure 11 the mapping results from the COSMO-CML/A1B scenario run for the future period 2020-2051 are compared with the COSMO-CML current climate control run 1986-2015 for the study region Waidhofen: The average number of heavy precipitation days per year rises from 0.87 – 2.43 up to 1.73 – 3.5 extreme events. The relative change ratios (bottom left image of Figure 11) range from 30 % in the east to 110 % in the north-west. In the central part, an increase of 60 to 70 % is expected. The highest numbers can be seen in the south and south-east, due to higher elevation. Thus, the changes range between 44 % (in the south-east) and 70 % (in the south-west). The spatial mean of all cells rises from 1.5 extreme event days per year to 2.43, and the overall average of the relative change is 62 %. In the municipality Waidhofen itself, the relative changes range from 33 % in the east to 90 % in the north-west.

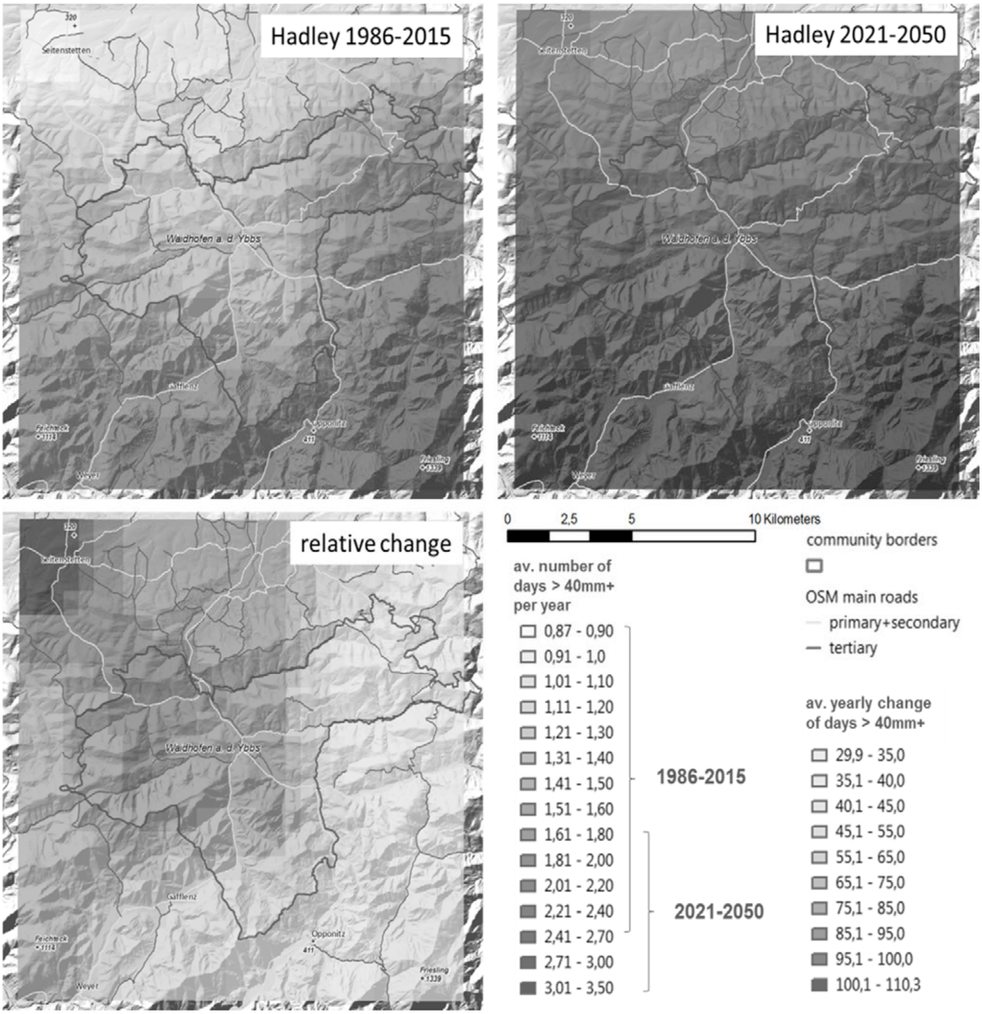


Fig. 11: Expected climate change signals for study region Waidhofen: Days with precipitation > 40 mm/day per year (30-year average) from COSMO-CML/HADCM3 control run 1986-2015 (top left), COSMO-CML/HADCM3 A1B scenario run 2021-2050 (top right), and relative change between future and reference period (bottom left). (Source: analysis of reclip:century simulations)

4 Conclusions and Outlook

Considering the climate change signals for extreme precipitation events, we can expect some substantial increase of climate related landslide risk.

In the study region Paldau, the heavy precipitation event occurrences start from a low baseline and the increase is expected to be rather moderate. Currently seven to nine heavy precipitation events are observed on average within a decade. In the period 2021-2050, up to three more events are expected within a decade, turning out as extreme event increase of up to 30 %, with low change rates in the higher elevated hilly north and higher change rates in the hilly south (starting from a lower baseline).

In the study region Waidhofen, the heavy precipitation event occurrences can be also expected to increase. The Ybbs valley shows under current climate around 12 heavy precipitation days within a decade, which is expected to increase up to 20 – 22 heavy precipitation days, resulting in a relative change of 70 to 90 %. In the forested mountain areas in the south with higher elevations, up to 30 extreme precipitation days within a decade can be expected. As this increase is expected for higher elevation ranges and steeper slopes, the increase of landslide risk seems to be severe. In general, the rainfall induced landslide risk in Waidhofen is, referring to absolute numbers, the two-fold of the risk in Paldau and is expected to increase up to the three-fold.

Figure 8 is important to discuss the overall outcome: estimations of changes of extreme precipitation events depend, because of the NAO precipitation oscillation, strongly on the selected periods to be compared. The study aims at exploring the near future 2021-2050, where we are expecting a low precipitation period. When moving the future target period to e. g. 2041-2070, the change signals of extreme precipitation days in the study regions would be much higher and so the landslide risk. We also must consider, that these results encompass principal uncertainty as they are extracted from a single regional climate simulation run with specific forcing data referring to a single GHG scenario, unless the results show good general agreement with the other simulations from the reclip: century ensemble.

In the future, it will be necessary to: (1) examine other target periods of this simulation run, (2) to repeat this analysis exploring other high resolution regional climate simulations based on different forcing data, applying different climate scenarios to improve the uncertainty assessment, (3) to examine extreme event patterns in different areas on both sides of the Alpine main ridge and within the inner Alpine valleys, and (4) to examine further climate related pre-conditions aside from heavy rainfall such as wet periods. These additional activities would bring deeper insights on the local impact of future extreme precipitation events for different periods and different regions.

This article concentrates on climate induced triggers of land slide risk. Orographic, geologic, soil and land-use/land cover – related triggers are explored in the project by another team, which is still working on the topic.

The project is funded under the Austrian Climate program (ACRP 9). We would like to thank the Climate and Energy fund for providing the financial resources to work on this project.

References

Loibl, W., Formayer H., Truhetz, H., Schöner, W., Anders, I., Gobiet, A., Heinrich, G., Kurshid, A., Nadeem, I., Peters-Anders, J., Schicker, I., Suklitsch, M., & Züger J. (2013) *Reclip:century-simulations:regional climate scenarios for the Greater Alpine Region till 2100*. Klimatag 2013. Retrieved Jan, 28, 2019, from https://www.ccca.ac.at/fileadmin/00_DokumenteHauptmenue/03_Aktivitaeten/Klimatag/Klimatag2013/Vortraege_14.Klimatag/V02_Loibl.pdf.

Auer, I., Chimani, B., Ganekind, M., Andre, K., Lexer, A., & Hiebl, J. (2015). *Homogenization of Austrian and Alpine time series.* Retrieved Jan 1, 2019, from http://www.zamg.ac.at/histalp/download/conferences/201506_READING.pdf.

Böhm, R. (2009). Klimarekonstruktion der instrumentellen Periode – Probleme und Lösungen für den Großraum Alpen. *Paldat Proceeedings,* 1–15. Retrieved Jan 28, 2019, from http://www.zamg.ac.at/histalp/download/abstract/Boehm-2009-draft-F.pdf.

Bundesministerium für Nachhaltigkeit und Tourismus (BMNT) (2015). Hydrographisches Jahrbuch. Retrieved Jan 28, 2019, from https://www.bmnt.gv.at/wasser/wasser-oesterreich/wasserkreislauf/ hydrographische_daten/jahrbuecher/jahrbuch2015.html.

BMNT (2019). Abt. Wasserhaushalt: Hydrogr. Dienst, HD-Messststellen. Retrieved Jan 28, 2019, from https://ehyd.gv.at/; https://wasser.umweltbundesamt.at/hydjb/.

CCCA (2019). CCCA data center – ÖKS15 *Climate Scenarios for Austria*. Retrieved Oct 28, 2019, from https://data.ccca.ac.at/group/oks15.

Glade, T. (2001). Landslide hazard assessment and historical landslide data – An inseparable couple? In: *The use of historical data in natural hazard assessments* (pp. 153–168). Dordrecht: Springer.

Hydrographischer Dienst (2019). *Hydrograph. Jahrbuch*.

Hitz, H., & Birsak, L. (2004). Klimatypen Österreichs (1961-1990). *Hölzel Universalatlas*.

National Weather Service – Weather prediction Center (2019). *North Atlantic Oscillation* (NAO). Retrieved Jan 31, 2019, from https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml.

IPCC (2007). *Climate Change 2007: Synthesis Report.* Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [R. K. Pachauri, & A. Reisinger (Eds.)]. IPCC, Geneva, Switzerland, 104 pp. Retrieved Jan 28, 2019, from https://www.ipcc.ch/report/ar4/syr/.

IPCC (2014). *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 [R. K. Pachauri, & L. A., Meyer (Eds.)]. IPCC, Geneva, Switzerland, 151 pp. Retrieved Jan 28, 2019, from https://www.ipcc.ch/report/ar5/syr/.

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

Pfahl, S. (2014). Characterising the relationship between weather extremes in Europe and synoptic circulation features. *Nat. Hazards Earth Syst. Sci*., *14,* 1461–1475.

Rockel, B., Will, A., & Hense, A. (2008). The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, *17*(4)*,* 347–348.

Reichenbach, R., Günther, A., & Glade, T. (2013). Landslide hazard and risk assessment at different scales. *Nat. Hazards Earth Syst. Sci*., *13*, 2169–2171.

Zentralanstalt für Meteorologie und Geodynamik – ZAMG (2019). *HISTALP – (Historical Instrumental Climatological Surface Time Series of the Greater Alpine Region – Database.* Retrieved Jan 28, 2019, from http://www.zamg.ac.at/histalp/.