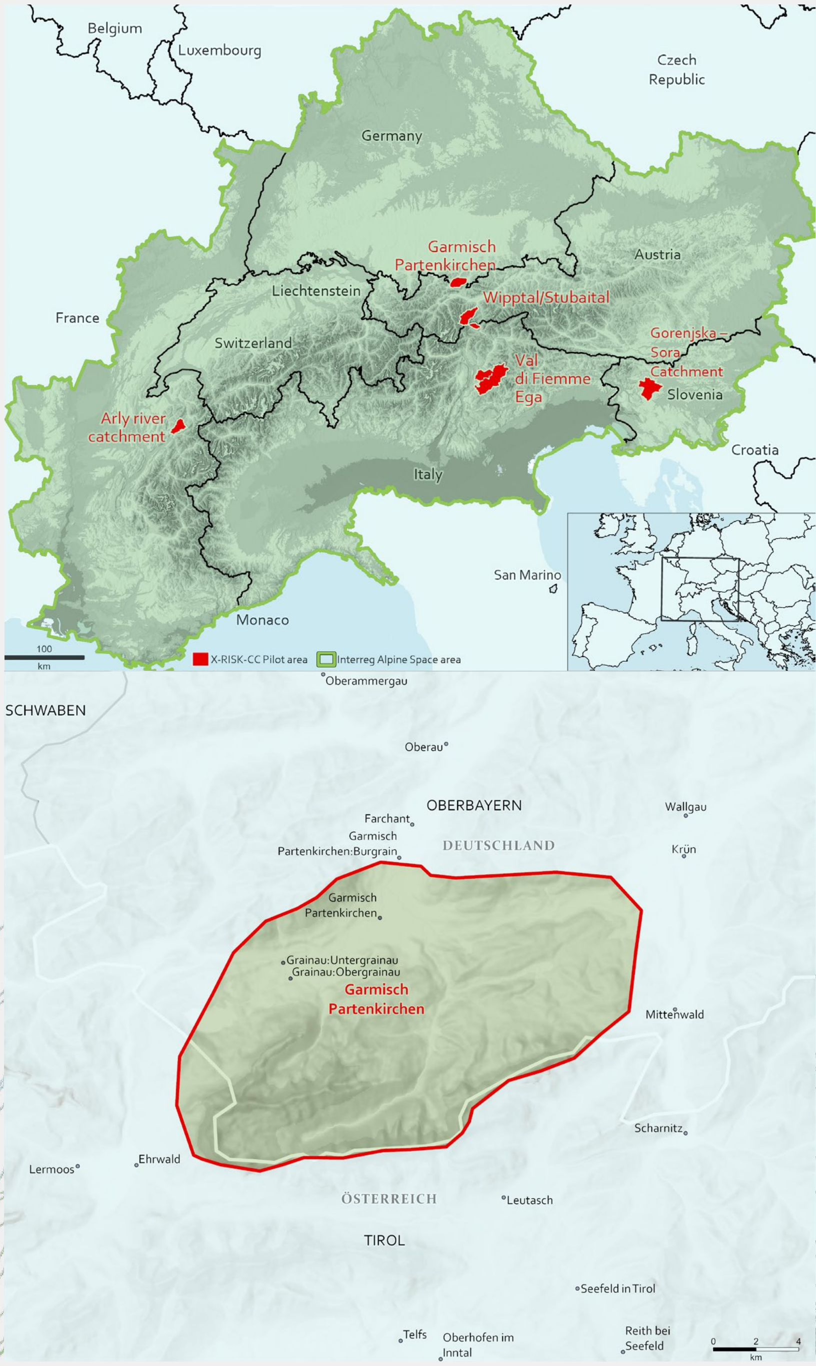

X-RISK-CC pilot areas (top) and the pilot area of Garmisch-Partenkirchen (bottom)

Interreg Co-funded by the European Union
Alpine Space

X-RISK-CC

SHORT-DURATION RAINFALL EXTREMES LEADING TO CASCADING AND COMPOUND MASS MOVEMENTS IN GARMISCH-PARTENKIRCHEN

Germany

Pilot report prepared by EURAC Research, Slovenian Environment Agency and GeoSphere Austria with the support of the X-RISK-CC partnership

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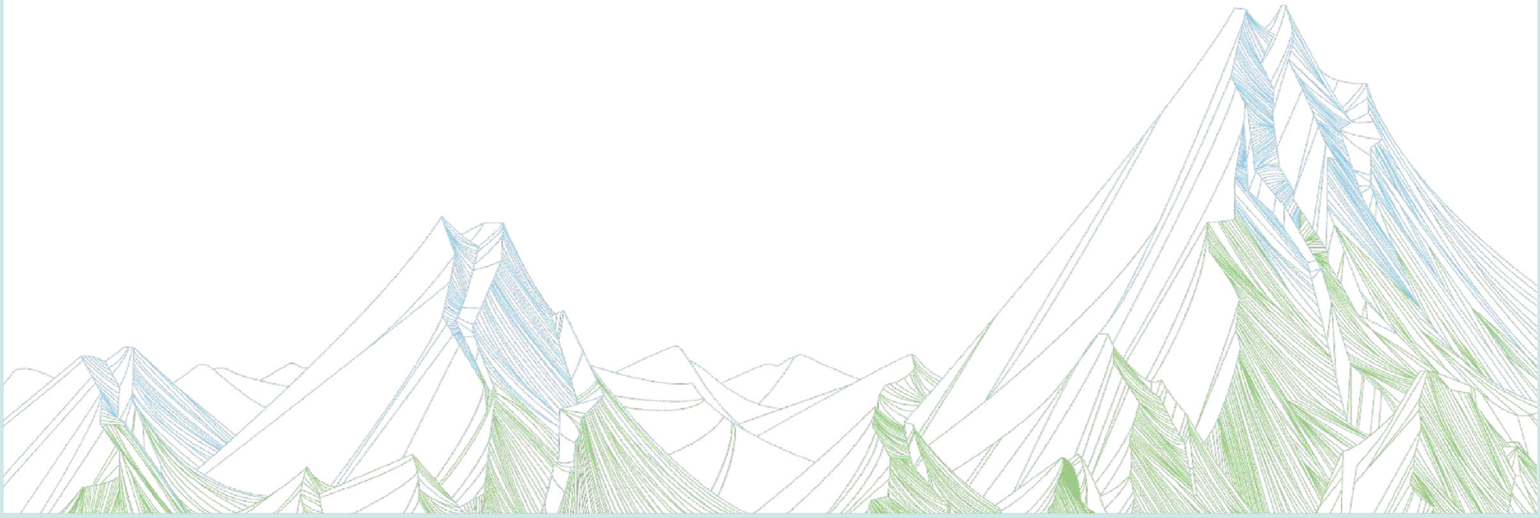


KEY MESSAGES

- The intensity and frequency of daily precipitation extremes do not show statistically significant changes over 1950–2022 in Garmisch-Partenkirchen area on both yearly and seasonal level, except for the high-elevation site of Zugspitze where annual precipitation maxima report an increasing trend. Hourly precipitation events at the observation site in Garmisch increased over the period 2000–2023 by + 4.3 events/decade on an annual scale and + 1.8 events/decade in summer.

- The frequency of the circulation types associated with the typical summer precipitation events in the area reports a weak reduction over the last 70 years but with no statistical significance.

- Daily precipitation extremes will become more frequent and intense in the future: under a global warning level of + 4 °C (GWL4), the projections for Garmisch report 12 to 25 more extreme precipitation days in a year and + 13% more intense events (i.e., from 64 mm to 70 mm as daily maxima) with respect to 1991–2020. The changes in frequency and intensity of summer extremes are still positive in most cases but less pronounced and associated to a larger model uncertainty.

- As consequence, the return levels of annual maxima of daily precipitation are expected to increase for all sites and return periods. For instance, the return levels associated with a 100-year recurring event are expected to be 41 % higher in Garmisch (i.e., from 164 mm to 213 mm) under GWL4 with respect to 1971–2020.

- Starting from the physical consideration that a warmer atmosphere holds a greater amount of moisture, hourly precipitation intensities are also projected to increase in the future. In particular, the 99th percentile of hourly precipitation at the station locations is expected to increase in the range of + 30 % for GWL1.5 and +380 % for GWL5.

PAST EXTREME EVENTS IN FOCUS

EPISODES OF SHORT-DURATION RAINFALL EXTREMES IN GARMISCH-PARTENKIRCHEN IN RECENT DECADES, LEADING TO COMPOUND AND CASCADING MASS MOVEMENTS

The pilot area of Garmisch-Partenkirchen was hit over past years by several episodes of intense precipitation of short duration which led in most cases to gravitational mass movements of different levels of severity. One of the most relevant episodes occurred on 22nd August 2005 when compound hazards, including debris flows and flash flood, were triggered by intense rainfall. On the day of the event, precipitation totals exceeded 100 mm at most weather station sites in the area. In Garmisch the estimated return period of the summer event was of ~ 90 years. More recent summer episodes of intense precipitation of short duration triggering flash floods in the area occurred in 2018, 2020 and 2021.

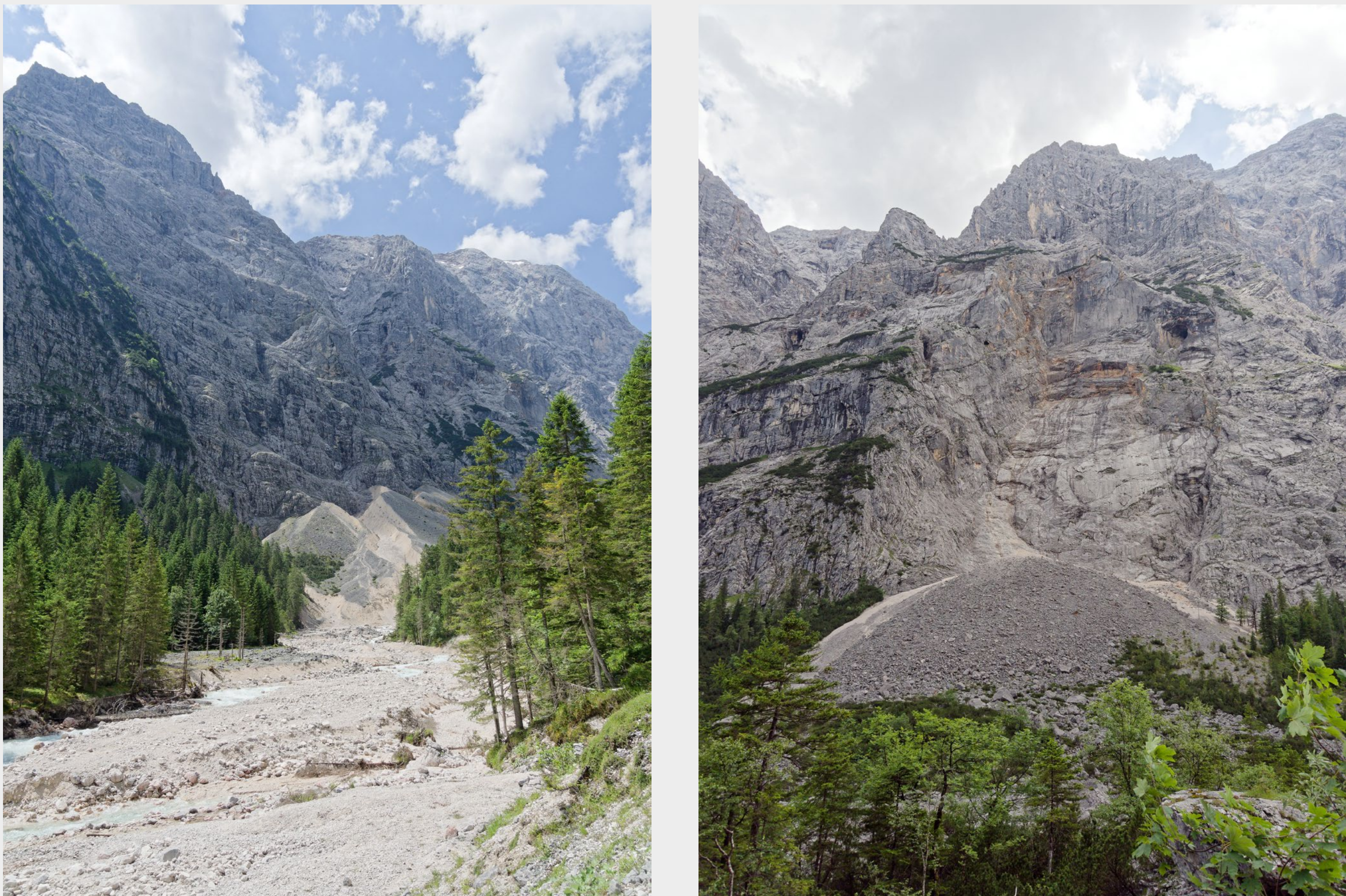


FIGURE 1: *Mass movement events in Garmisch-Partenkirchen (Author: Benjamin Jacobs).*

DEFINITION OF METEOROLOGICAL EXTREMES

EXTREME PRECIPITATION

Rx1d: annual, summer (June to August, JJA) and autumn (September to November, SON) precipitation maxima over 1 day.

R97pN_1d: annual, summer and autumn number of days with precipitation exceeding the 97th percentile of the reference period (1991–2020) considering wet days (daily precipitation ≥ 1 mm).

Rx1h: annual and seasonal precipitation maxima over 1 hour.

R99pN_1h: annual and seasonal number of events with hourly precipitation exceeding the 99th percentile of the reference period 2000–2020 (only considering hourly precipitation ≥ 0.1 mm).

DATA

For the pilot area of Garmisch-Partenkirchen, observations of daily precipitation at 3 stations were used for the analysis of extreme 1-day precipitation events in the period from 1950 to 2022, namely Garmisch-Partenkirchen (704 m above sea level, a.s.l.), Mittenwald-Buckelwiesen (983 m a.s.l.) and Zugspitze (2'956 m a.s.l.). All datasets completed operational quality control by the data provider DWD (German Meteorological Office) but did not undergo homogenization, therefore the time series can include inhomogeneities (caused by e.g., changes in station location or instruments). This should be taken into account when interpreting the results, especially for temporal trend analysis. There is a very small number of missing data in the studied period (less than 0.2 % per station). In addition to daily data, hourly precipitation data at Garmisch-Partenkirchen station in the period 2000–2023 were also analysed. As for daily data, the hourly series was quality controlled until 2022 by DWD, whereas recent data have not yet completed the full quality control.

For the assessment of future climate, daily precipitation projections from 9 EURO-CORDEX simulations (***TABLE 1***) were adjusted on local station data and used for the analyses. The models were selected based on the reference EURO-CORDEX ensemble adopted by DWD (https://www.dwd.de/DE/leistungen/klimaprojektionen/referenz-ensemble_tabelle.html).

TABLE 1: *List of EURO-CORDEX simulations considered for the assessment of future changes in daily precipitation extremes in the Garmisch-Partenkirchen pilot area.*

	Global Climate Model	**Regional Climate Model** (Institute)
1	EC-EARTH	CCLM4-8-17 (CLMcom)
2	EC-EARTH	RACMO22E (KNMI)
3	EC-EARTH	RCA4 (SMHI)
4	IPSL-CM5A-MR	RCA4 (SMHI)
5	HadGEM2-ES	CCLM4-8-17 (CLMcom)
6	HadGEM2-ES	RACMO22E (KNMI)
7	HadGEM2-ES-LR	RCA4 (SMHI)
8	MPI-ESM-LR	CCLM4-8-17 (CLMcom)

TYPICAL SYNOPTIC SITUATION LEADING TO THE EXTREME EVENT

The prevailing circulation type for the Garmisch-Partenkirchen event of 22nd August 2005 is GWT 17 ('Gross-Wetter-Type'; a circulation type classification).This circulation pattern is shown in ***FIGURE 2***. It is characterized by a low-pressure system over Central Europe. The specific ERA5 field for the day the event was happening is shown in ***FIGURE 3***. Besides the low-pressure system over the Alps, it also shows a cut-off low in the geopotential height field at 500 hPa. This leads to strengthened lift, which is the cause for heavy precipitation. ***FIGURE 4*** shows the count of GWT 17 per year (only during summer – JJA). There is a tendency to slightly less events. However, this only depicts the circulation and hence the dynamic factor for frequency and says nothing about the magnitude of such events.

Note that GWTs only capture the large-scale circulation of the weather situation and serve as preconditioning for extreme weather events. However, the existence of a specific GWT class alone does not entail extreme weather events all the time. There are more fine-grained details and thermodynamic components that also play a role in any specific weather situations. Nevertheless, the GWT analysis allows to estimate large-scale circulation changes and therefore changes to the preconditioning relevant for extreme weather events.

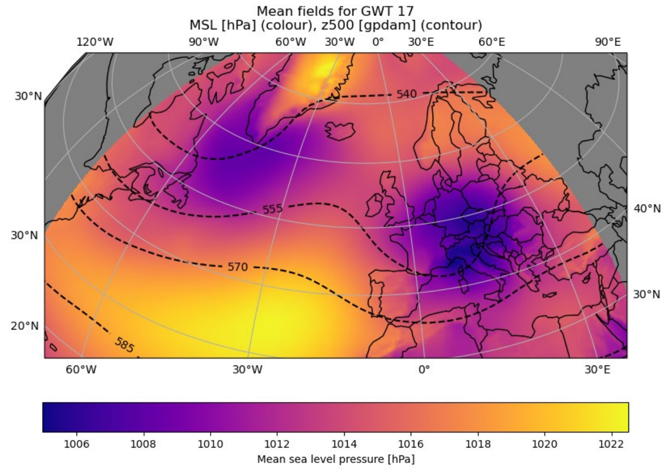


FIGURE 2: *Prevailing GWT for Garmisch-Partenkirchen: GWT 17. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

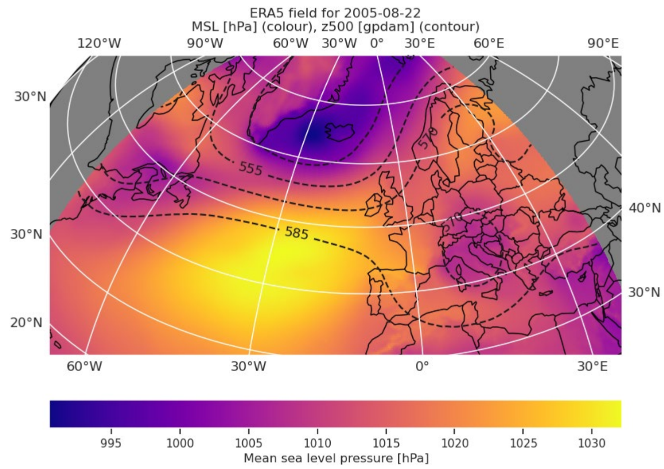


FIGURE 3: *Mean sea level pressure and geopotential height in 500 hPa for the Garmisch-Partenkirchen event in 2005 based on ERA5 reanalysis data. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

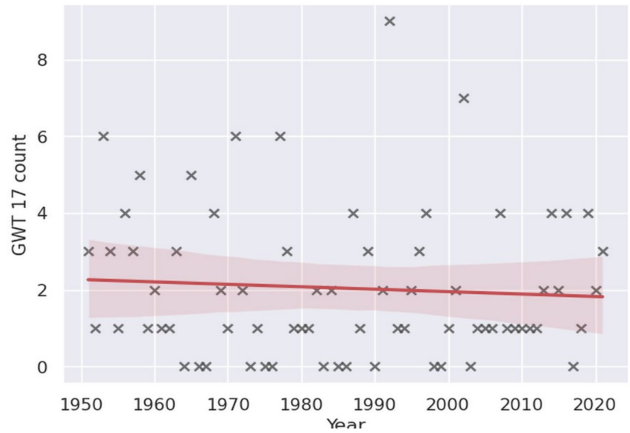
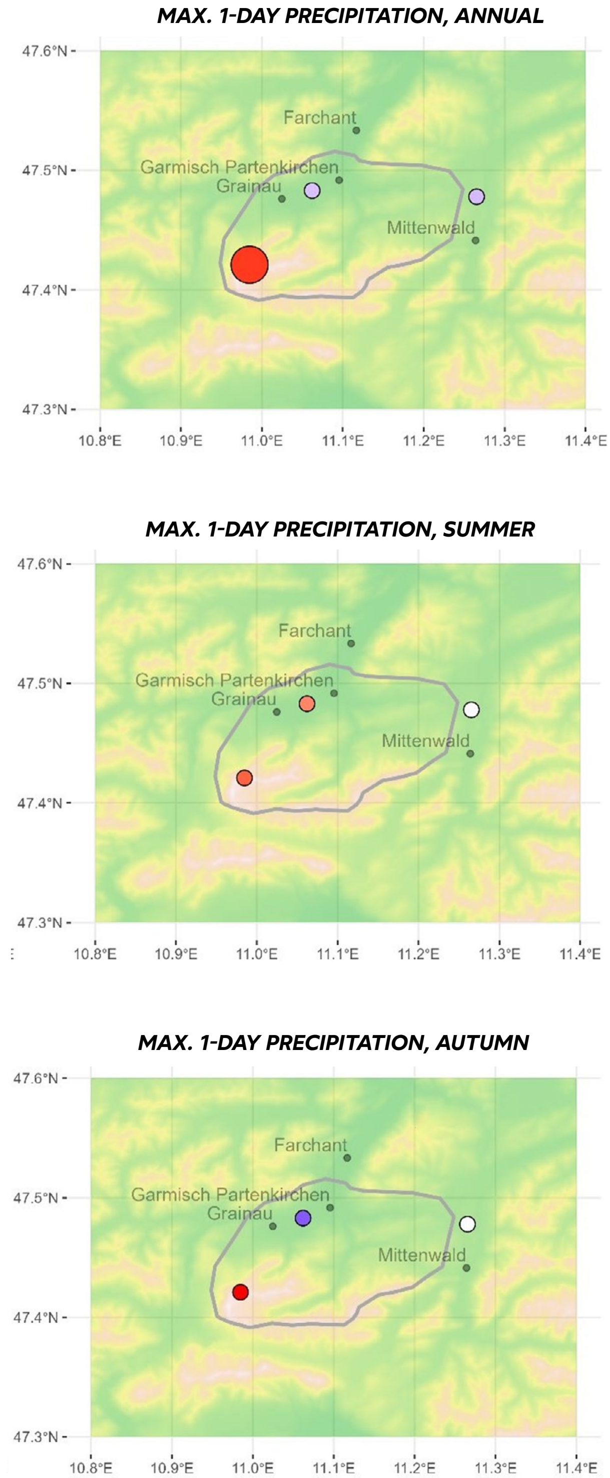


FIGURE 4: *GWT 17 counts for summer for each year. No significant trend can be seen from historical data, but there is a tendency to decrease of such circulation patterns. Note that this only depicts the dynamic component, i.e. circulation, that is associated with that event.*

CHARACTERISTICS OF EXTREME EVENTS IN THE PAST

Linear trends in the frequency of 1-day precipitation extremes (R97pN_1d) show no statistical significance, regardless of the season. The frequency of extreme precipitation days in the Garmisch pilot area therefore does not show significant change over time. Precipitation intensity, defined as the annual or seasonal maximum of 1-day precipitation (Rx1d), shows significant increase over time mainly for the high-altitude station Zugspitze. A significant positive trend from 1950 to 2022 is observed on an annual scale with + 2.5 %/decade (***FIGURE 5***), while for summer an increasing tendency is found but with no statistical significance.

On a sub-daily scale, which is more directly related to convective summer rainstorms, only trends for Garmisch-Partenkirchen station in the period 2000–2023 were analysed due to insufficient data availability (continuous data record of at least 20 years) and data quality at the other two stations. The number of precipitation events with hourly precipitation exceeding the 99th percentile of the reference period 2000–2020 (R99pN_1h) shows statistically significant positive trend with + 4.3 events/decade on an annual scale and + 1.8 events/decade for summer at 95 % confidence level, thus, approximately half of the annual trend can be attributed to increasing occurrence of intense hourly precipitation events in summer. The intensity of hourly precipitation maxima (Rx1h) shows statistically significant positive trends for autumn and winter with approximately + 2.1 mm/decade and + 0.7 mm/decade respectively.



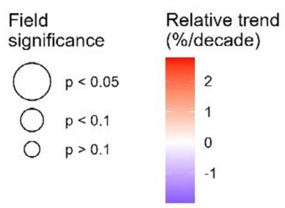


FIGURE 5: *Relative trends in 1-day precipitation maximum on an annual (top left), summer (top right) and autumn (bottom) level in the period 1950–2022. Trends are expressed as % / decade, the color refers to the magnitude of trend while the point size represents the significance level of the trend.*

Rx1d

WHAT TO EXPECT IN THE FUTURE?

The frequency of extreme precipitation days is expected to increase in the future on an annual scale across the pilot area (***FIGURE 6***). The number of days in a year with daily precipitation above the 97th percentile of the reference period increases with the level of global warming, reaching between 12 to 25 more extreme precipitation days in a year, as median of the model ensemble, under GWL4 with respect to 1991–2020, depending on the location. As for past observations, the high-altitude station of Zugspitze is expected to experience the greatest increase in the frequency. The changes are less pronounced for summer, where the greatest increase in the frequency is expected under GWL3 with up to 12 more extreme precipitation days with respect to the present conditions, however, there is a greater uncertainty associated with changes in summer (larger model spread).

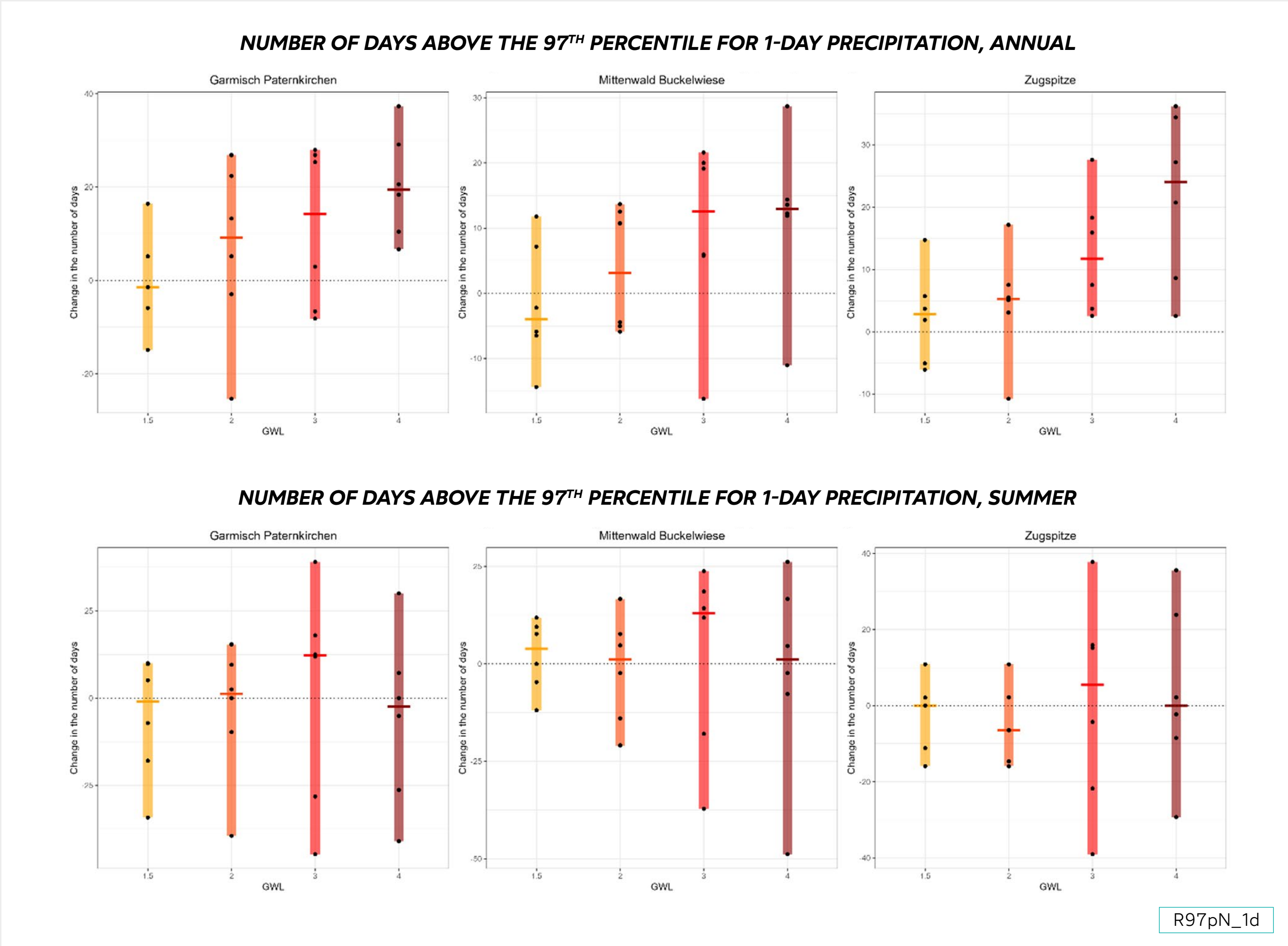


FIGURE 6: *Projected changes in the number of days with precipitation above the 97th percentile for four global warming levels relative to 1991–2020 on an annual level (top) and for summer (bottom) at the three station locations in the pilot area. The bars show the range and the median of the changes reported by the model ensemble.*

As regards the intensity of daily precipitation extremes (Rx1d), increases with respect to the reference period 1991–2020 are projected for all sites especially under the worst-case scenarios GWL3 and GWL4 (***FIGURE 7***). In particular, under GWL4 the intensity of 1-day precipitation summer maxima is projected to increase of about 7 % and 8 % in Garmisch and Mittenwald, respectively, and of about 5 % at Zugspitze station, as median of the model ensemble. The projected increases are slightly higher if annual 1-day precipitation maxima are analysed. For Garmisch-Partenkirchen station, the median projected increase in the intensity of the 1-day precipitation maxima ranges between 1 % (GWL1.5) and 13 % (GWL4). Similar findings are obtained for Mittenwald, while the projected changes are within + 6 % for Zugspitze. In ***FIGURE 7***, the full range of future changes in annual Rx1d projected by all model simulations is reported for each station site. It is worth noting that the spread of projected changes remains large and in some cases reductions in the intensity of Rx1d are reported by a portion of the model simulations.

Similarly, projected changes in return levels of annual 1-day precipitation maxima are positive, as median of all model simulations, for all sites and return periods, especially under higher global warming levels (figure not shown). In particular, the return levels associated with a return period of 100 years are projected to increase between 33 % and 41 % in Garmisch and between 15 % and 37 % in Mittenwald under GWL3 and GWL4, respectively.

To investigate sub-daily precipitation changes, we use the Clausius-Clapeyron relationship stating that the moisture-holding capacity in the atmosphere increases at a rate of around 7 % °C^{-1}. In a warmer climate an intensification of extreme precipitation events is thus expected due to the greater water vapour in the atmosphere. Based on this principle, hourly precipitation values in the future are scaled based on projected temperatures in the Alps. This represents an estimate to the potential increase in extreme precipitation, assuming there is enough moisture available

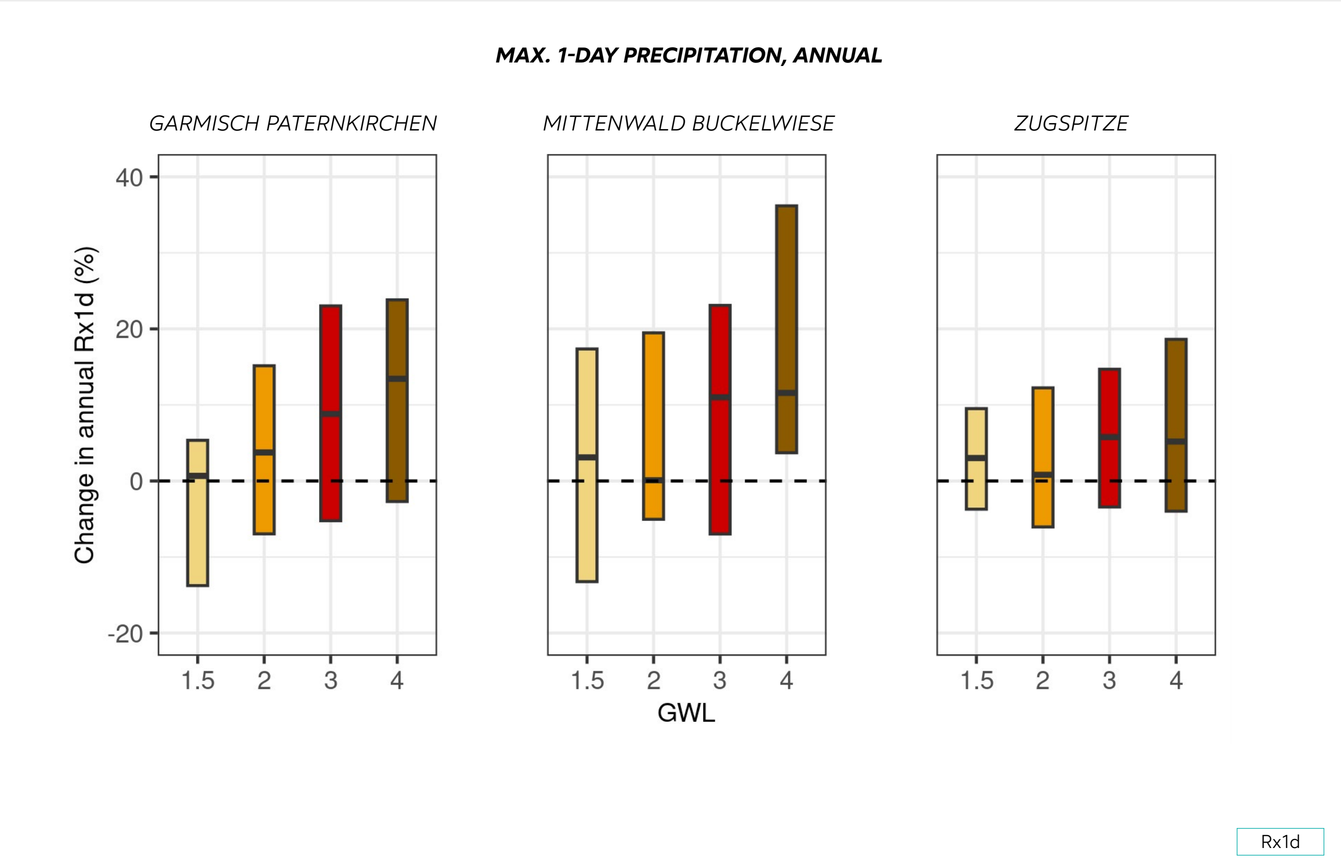


FIGURE 7: *Projected changes in the intensity of annual 1-day precipitation at the three station locations in the Garmisch-Partenkirchen pilot area under different Global Warming Levels (GWLs). Values are reported as percentage changes with respect to 1991–2020 and the bars report the range and the median of projected changes by the model ensemble.*

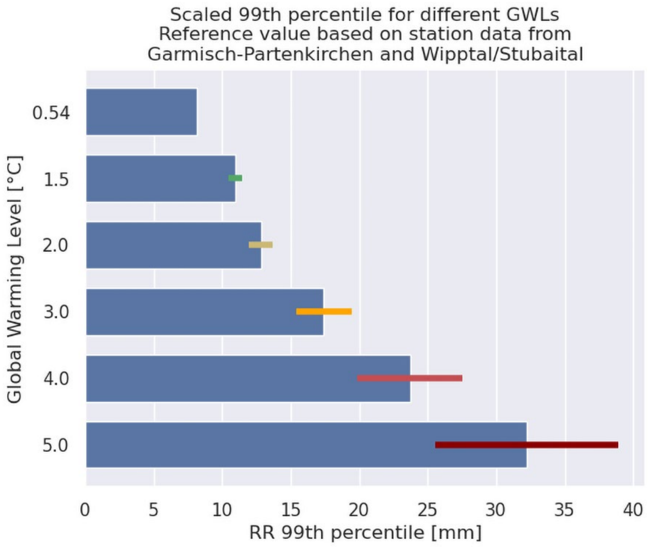


FIGURE 8: *Scaled 99th percentile of hourly precipitation rates for different GWLs. The first row depicts the current Warming Level according to the 30-year period 1991 to 2020.*

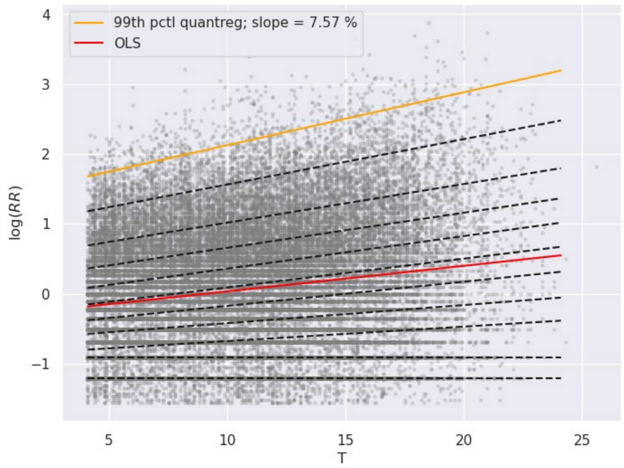


FIGURE 9: *Quantile and least squares regression for all station data from Garmisch and Wipptal/Stubaital for RR > 0.2 and T > 4 (these two filters reflect using only wet days and days outside winter). The regressed 99th percentile yields a slope of ~ 7.6 %, which is in rough agreement with Haslinger et al. (in prep.) for a more robust Alpine scale precipitation scaling that is used above.*

R99pN_1h

(more details are reported in the Methodology section). Results yield increases of ~ 28 % for the lower bound of GWL1.5, up to ~ 380 % for the upper bound of GWL5. In absolute terms, it means that the 99th percentile of hourly precipitation (computed on the values of all stations in Wipptal/Stubaital and Garmisch) increases from 8.2 mm in the reference period to ~ 10.5 mm up to ~ 39.6 mm, respectively. The scaled 99th percentile of hourly precipitation including error bars are shown in ***FIGURE 8***. It is evident (and follows from the definition of pattern scaling), that the uncertainty grows with higher GWLs. All station data located in the pilot areas of Wipptal/Stubaital (IT-AT) and Garmisch-Partenkirchen are used to validate the precipitation scaling factor applied. The result is shown in ***FIGURE 9***, which depicts the scaling of different quantiles from the logarithm of hourly precipitation vs. near-surface station temperature. The scaling factor for the 99th percentile of precipitation (~ 7.6 % C^{-1}) agrees with more robust Alpine scale estimates obtained by Haslinger et al. (in preparation).

METHODOLOGY

GENERALIZED EXTREME VALUE DISTRIBUTION (GEV) AND ESTIMATION OF RETURN PERIODS OF EXTREME EVENTS

The GEV distribution is a family of continuous probability distributions developed within extreme value theory. Extreme value theory provides the statistical framework to make inferences about the probability of very rare or extreme events.

If we have large number of independent observations, $X_1, X_2, \ldots$, we can block them into sequences of observations of length n. We then get a series of block maxima $M_{n,1}, \ldots M_{n,m}$ of length m. In our case X_i represents e.g. daily sum of precipitation. If n is the number of observations in a year, then $M_{n,i}$ corresponds to the annual maximum. For some large value of m (which in our case corresponds to number of years) Generalized Extreme Value distribution (GEV distribution) can be fitted to distribution of $M_{n,m}$ (Coles, 2001).

The GEV distribution unites the Gumbel, Fréchet and Weibull distributions (also known as type I, II and III extreme value distributions) into a single family and is defined as:

$$G(x;\mu,\sigma,\xi) = \begin{cases} e^{-(1+\xi\frac{x-\mu}{\sigma})^{-\frac{1}{\xi}}}, & \xi \neq 0, \\ e^{-e^{\frac{x-\mu}{\sigma}}}, & \xi = 0 \end{cases}$$

where $1+\xi\,\frac{x-\mu}{\sigma} > 0,\ \mu,\sigma \in R$ in $\sigma > 0$.

The GEV distribution is parameterized with three parameters:

- Location parameter (μ), which determines the location or shift of the distribution.
- Scale parameter (σ), which determines the scale or statistical dispersion of the probability distribution.
- Shape parameter (ξ), which controls the shape and size of the tails of the three different families of distributions subsumed under it. Values $\xi > 0$ corresponds to the Fréchet distribution, $\xi < 0$ corresponds to the Weibull distribution and $\xi = 0$ corresponds to Gumbel distribution.

Estimates of extreme quantiles of the annual maximum distribution are obtained by inverting the previous equation:

$$z_p = \begin{cases} \mu - \frac{\sigma}{\xi}\left[1 - \{-\log(1-p)\}^{-\xi}\right], & \xi \neq 0, \\ \mu - \sigma\, log\{-\log(1-p)\}, & \xi = 0, \end{cases}$$

Where $G(x_p) = 1 - p$. In the common terminology, z_p is the return level associated with the return period $1/p$. More precisely, z_p is exceeded by the annual maximum in any particular year with probability p.

TREND ASSESSMENT OF EXTREME EVENTS

The trends of climate indices are based on quality-controlled time series of meteorological measurements at observing stations. The selection of time series for the calculation of climate indices and trends (number of days above/below threshold, extreme values) is based on two criteria: no large breaks or missing data in time series and adequate quality of daily data. Details on the data series selection are provided in the Data section. Linear trend in time series is calculated by Theil-Sen method, which is known for its robustness for asymmetric and heteroscedastic residuals in linear regression (Theil, 1950; Sen, 1968). Statistical significance of the trend is calculated by the Mann-Kendall test and is based on the 95 % confidence interval (Mann, 1945; Kendall, 1975). The trend is different from zero at 5 % significance level if the sign of the whole confidence interval is the same. The collective significance of the trends on a given pilot area (field significance) is evaluated from individual significance tests, controlling the false discovery rate (Wilks, 2016).

PROJECTED CHANGES UNDER GLOBAL WARMING LEVELS

The projected changes in the pilot area are assessed for different levels of global warming by considering the available EURO-CORDEX projections listed under Data. The global warming levels (GWLs) considered are + 1.5, + 2, + 3 and + 4 °C with respect to the pre-industrial baseline period 1850-1900, following the approach included in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021). For each GWL, the corresponding 20-year period when global mean temperature reaches that level of increase with respect to the baseline period is identified for each model and RCP (Representative Concentration Pathway) simulations (https://github.com/mathause/cmip_warming_levels). Since some models and RCP scenarios does not include all GWLs, only the RCP 8.5 simulations covering all considered GWLs are considered.

It is important to note, that GWLs cannot be translated into a specific temporal interval since it varies among the models. However, for assigning a temporal horizon to projected results, the highest GWL3 and GWL4 are reached by models in the second half of the 21st century under high emission scenarios.

For the assessment of future changes, the 20-year interval associated with each GWL is considered and extended over a 30-year period by adding 5 years before and after the GWL interval. The changes are evaluated with respect to the 1991-2020 baseline. For the assessment of future return levels, the 20-year GWL interval is extended over a 50-year period by adding 15 years before and after the 20-year interval. The changes are evaluated with respect to the 1971-2020 baseline.

ANALYSIS OF SYNOPTIC CONDITIONS OF PILOT EVENTS

Mean sea level pressure (MSLP) data from 80° West to 40° East and 30° to 70° North for the last 70 years from the ERA5 reanalysis is used to calculate 'Gross-Wetter-Typen' (GWT), which is a circulation type classification and is based on correlations between mean sea level pressure fields that are grouped into 18 clusters. The COST733 (Philip et al., 2014) software is used for that. Specific pilot events are then characterised by the mean GWT pattern derived over 7 decades of ERA5 data and by analysing the specific daily MSLP pattern at event occurrence. Furthermore, for the specific season when the event has happened, trends in GWT occurrences over the 70-year period are evaluated with a 99 % confidence interval.

ANALYSIS OF SUB-DAILY PRECIPITATION CHANGES

Based on the Clausius-Clapeyron relationship, that relates temperature and moisture, hourly precipitation values are scaled based on temperature. This represents an estimate to the potential increase in precipitation, assuming there is enough moisture available. We scale temperature based on previous work (Schröer and Kirchengast, 2018 and Haslinger et al., in prep), which established a temperature scaling for hourly precipitation of about ~ 7.3 % (± 1.1 %) per degree of warming. This scaling factor relates temperature at stations to the logarithm of hourly precipitation values. To estimate future changes, we use Alpine Space Warming Levels (ASWL) to construct different scenarios. We set ASWL as twice the Global Warming Level (GWL), which roughly follows historical records.

To derive future estimates of hourly precipitation, we follow the following recipe:

- Find the current ([1991,2020]) level of Alpine space warming: $ASWL_{ref} = GWL_{ref} \cdot 2$
- Find the current 99th percentile of hourly precipitation rates: RR_{ref} (RR >0.2; wet days)
- Set the sought after GWL: $ASWL(GWL) = GWL \cdot 2$ (e.g., for $GWL = 2°C$, $ASWL\ (2°C) = 2°C \cdot 2 = 4°C$)
- Determine the scaling factor (F) based on the empirical relationship (including uncertainty) for the expected change: $F(GWL) = 1 + \left((0.073 \pm 0.011) \cdot (ASWL(GWL) - ASWL_{ref})\right)$
- Scale the reference precipitation value (with log-transform): $RR(GWL) = \exp\left(\log(RR_{ref}) \cdot F(GWL)\right)$

To validate the scaling factor, we pooled the available station data from Wipptal/Stubaital and Garmisch-Partenkirchen together, such that the estimated regional scaling factor is as robust as possible. Applying the quantile regression for the 99th percentile thereby showed a comparable scaling to previous work (Schröer and Kirchengast, 2018; Haslinger et al., in prep.). In total, 3 stations from Garmisch-Partenkirchen, covering 1994 to 2021, and 6 from Wipptal/Stubaital, covering 2001 to 2020, were used. Note that not every station covers the full range, some begin later while others end earlier.

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