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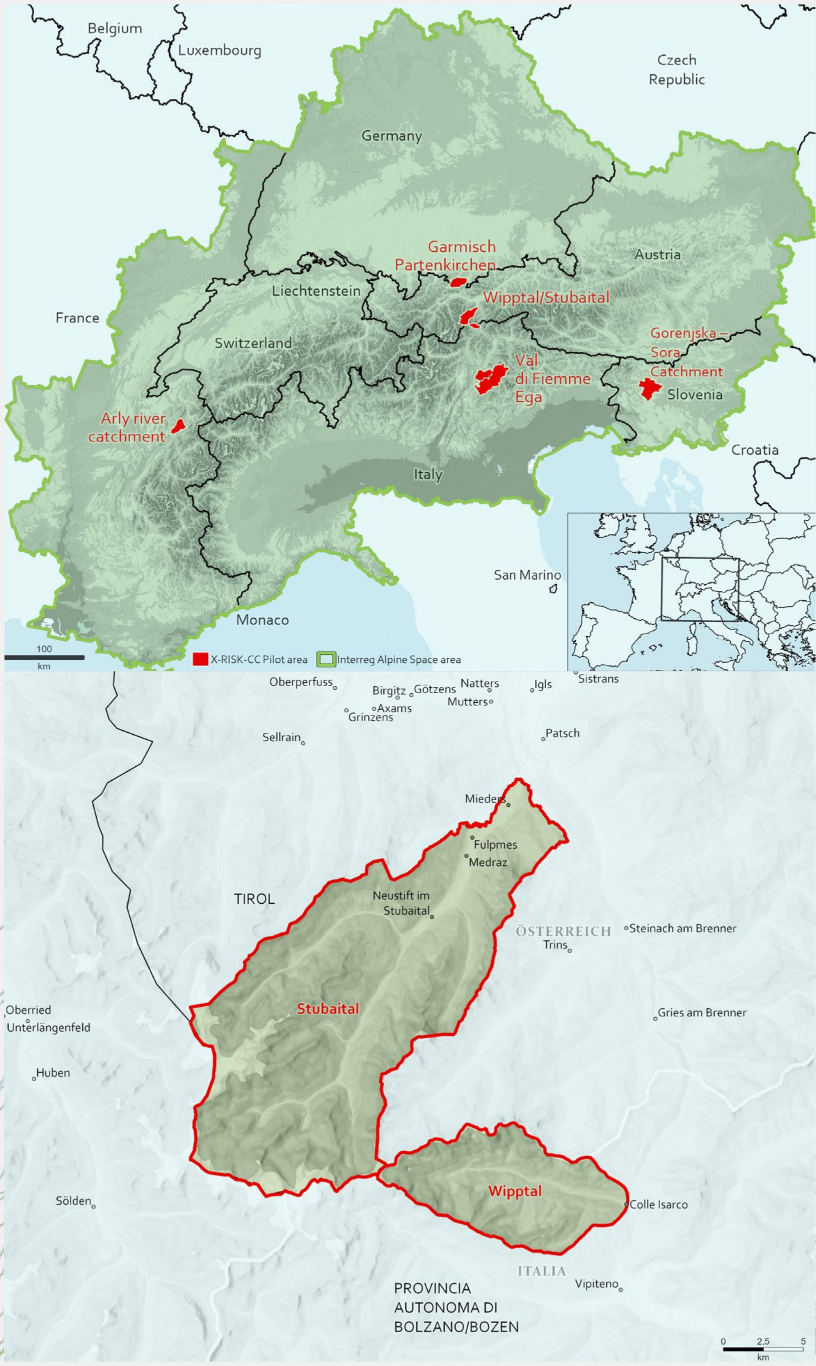

X-RISK-CC pilot areas (top) and the pilot area of Wipptal/Stubaital (bottom)

SHORT-DURATION RAINFALL EXTREMES LEADING TO GRAVITATIONAL MASS MOVEMENTS IN A TRANSBOUNDARY ITALIAN-AUSTRIAN AREA – WIPPTAL AND STUBAITAL

Italy / Austria

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

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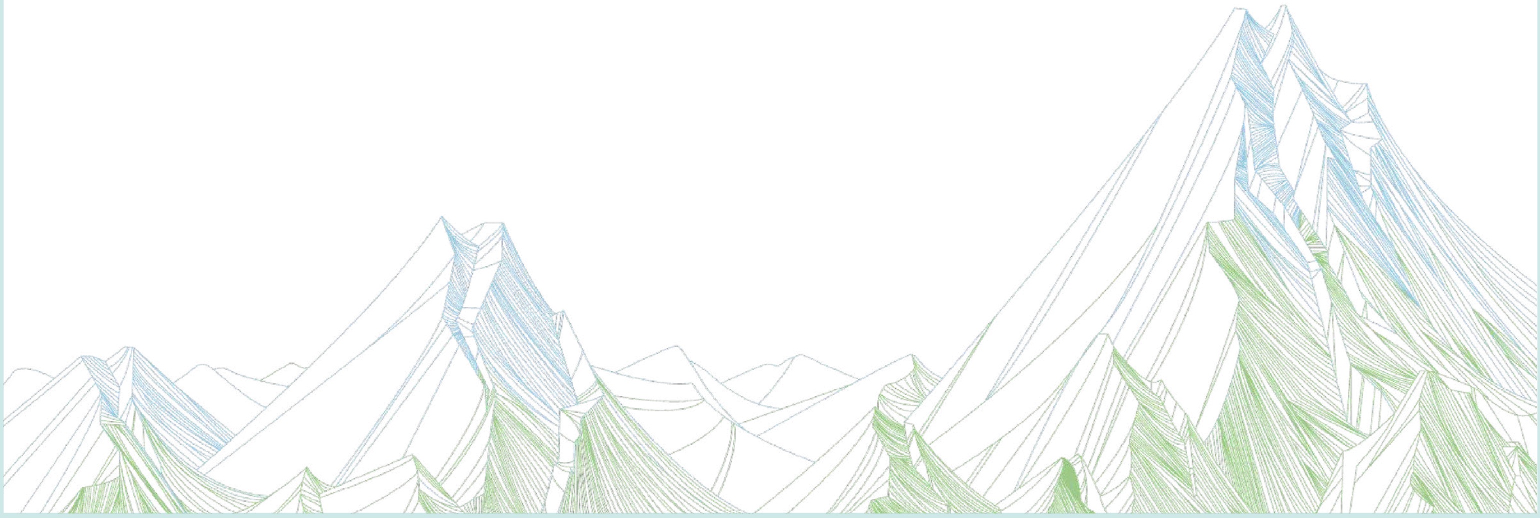

KEY MESSAGES

- Based on the station observations from 1980 to 2022, an overall tendency towards more intense and frequent 1-day precipitation extremes in the area was depicted for both annual and summer values. However, the trends have no statistical significance.
- The frequency of the circulation types associated with the typical intense precipitation summer events in the area does not show significant changes but only a weak reduction in the last 70 years.
- In the future the intensity of 1-day precipitation extremes is projected to increase in the whole area up to around + 15 % with respect to the 1991–2020 conditions if the worst scenario is considered, i.e. global warming level of + 4 °C (GWL4). Similarly, 1-day extremes are expected to become more frequent especially in Wipptal with a frequency increase for GWL4 of + 46 % in Wipptal and + 23 % in Stubaital with respect to the 1991–2020 conditions.
- Accordingly, the return levels of 1-day precipitation events of different rarity are projected to increase in the future over the whole area. For instance, a 50-year event in Stubaital is expected to become about 20 % more intense under GWL4 with respect to present conditions. In Wipptal a 50-year event is projected to become about 28 % more intense under GWL4.
- 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

SUMMER EPISODES OF SHORT-DURATION RAINFALL EXTREMES IN WIPPTAL (IT) AND STUBAITAL (AT) IN 2021 AND 2022, LEADING TO DEBRIS FLOWS AND OTHER MASS MOVEMENT TYPES

The Italian-Austria cross-boundary pilot area of Wipptal (IT) and Stubaital (AT) was hit over past years by several episodes of intense precipitation of short duration during the summer months. These events led in most cases to flood and gravitational mass movements of different levels of severity. An impactful event occurred on 16th August 2021 in the Wipptal area, when thunderstorms with heavy rain, exceeding 80 mm per day, caused a debris flow and, as a cascading effect, flooding with damage to buildings and infrastructure. In Stubaital, a heavy precipitation episode occurred on 22nd July 2022 with more than 100 mm per day recorded by local weather stations and triggered several debris flows damaging infrastructure and blocking several roads.

FIGURE 1: *Flood event of Toverino River in Wipptal on 16th August 2021 (Source: Civil Protection Agency of the Province of Bolzano).*

DEFINITION OF METEOROLOGICAL EXTREMES

EXTREME PRECIPITATION

Rx1d: annual and summer (June to August) precipitation maxima over 1 day.

R97pTOT_1d: annual and summer (June to August) sum of daily precipitation exceeding the 97th percentile computed over the reference period (1991–2020) considering only wet days (daily precipitation ≥ 1 mm).

R97pN_1d: annual and summer (June to August) number of days with precipitation exceeding the 97th percentile computed over the reference period (1991–2020) considering only wet days (daily precipitation ≥ 1 mm).

DATA

In the pilot area, daily precipitation data for 15 station locations were available from the Autonomous Province of Bolzano for Wipptal and from Geosphere Austria for Stubaital. All series have been already checked by the data providers and underwent additional quality checks to ensure the absence of outliers and the internal consistency. The analysis period considered is 1980–2022 and only a subset including the 11 longest and continuous stations is used for the trend and climatological analyses, while all series were included in the event description.

Sub-daily data were not used for the assessment of trends due to the limited temporal extent of the available series, while they were considered for the assessment of the specific events.

When analysing station observations, it is important to consider that they can be still affected by uncertainties, especially in areas characterized by a complex orography. In particular, precipitation amounts at high-elevation sites can be underestimated especially during episodes of strong wind speed.

For the future, daily precipitation projections from regional climate scenarios for Austria and Trentino-South Tyrol region were used. The regional products were based on EURO-CORDEX model simulations adjusted on observations and resampled on a 1-km grid.

The considered 5 GCM-RCM simulations in common between the regional scenario ensemble of Trentino – South Tyrol and the Austrian national scenarios are listed in ***TABLE 1***.

It is important to note that station observations and model simulations are not directly comparable, even after the bias-adjustment procedure, which increases the overall accuracy of model fields but does not increase the spatial scales resolved. The coarser spatial resolution of the model simulations thus limits the representation of local-scale features, especially in orographically-complex regions.

TABLE 1: *List of EURO-CORDEX models used for evaluation of projected changes of precipitation extremes in Wipptal and Stubaital. All simulations were bias-adjusted on local observations and are available at 1-km spatial resolution.*

	Global Climate Model	**Regional Climate Model** (Institute)
1	CNRM-CM5	CCLM4-8-17 (CLMcom)
2	EC-EARTH	CCLM4-8-17 (CLMcom)
3	HadGEM2-ES	CCLM4-8-17 (CLMcom)
4	MPI-ESM-LR	CCLM4-8-17 (CLMcom)
5	MPI-ESM-LR	REMO2009 (MPI-CSC)

TYPICAL SYNOPTIC SITUATION LEADING TO THE EXTREME EVENT

The prevailing circulation type for the event on 16th August 2021 in the pilot area of Wipptal/Stubaital is GWT 3 ('Gross-Wetter-Type'; a circulation type classification). This circulation pattern is shown in ***FIGURE 2***. It is characterized by a trough over Central Europe with corresponding low pressure across Central Europe. Precipitation for this circulation pattern can be wide ranged in the front of the through axis, due to lifting. The specific ERA5 field for the day when the event happened is shown in ***FIGURE 3***. The trough axis resides West of the Alps, which leads to a southerly flow and hence precipitation south of the Alpine ridge. ***FIGURE 4*** shows the count of GWT 3 per year (only during summer – JJA). There is a tendency to slightly less events over the last 70 years. 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 therefor changes to the preconditioning relevant for extreme weather events.

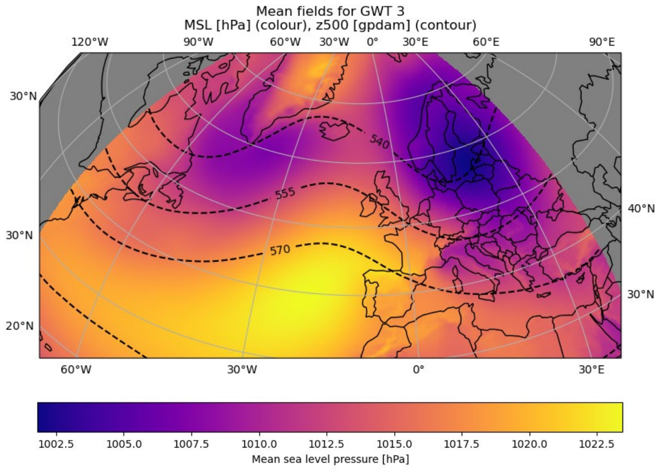

FIGURE 2: *Prevailing GWT for Wipptal/Stubaital: GWT 3. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

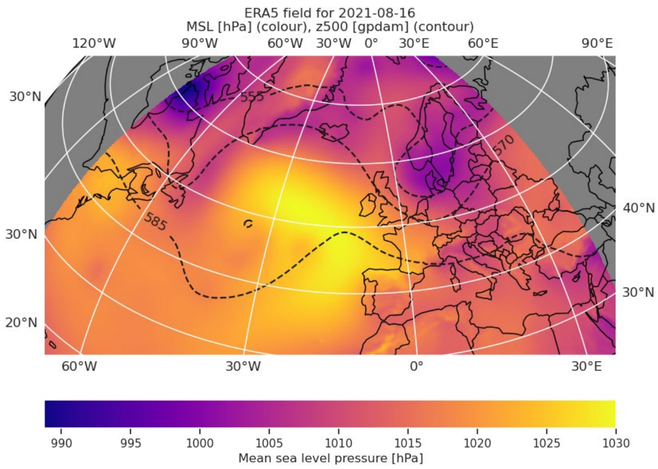

FIGURE 3: *Mean sea level pressure and geopotential height in 500 hPa for the Wipptal/Stubaital event in 2021 based on ERA5 reanalysis data. Mean sea level pressure is shown in colours, 500 hPa geopotential as contours.*

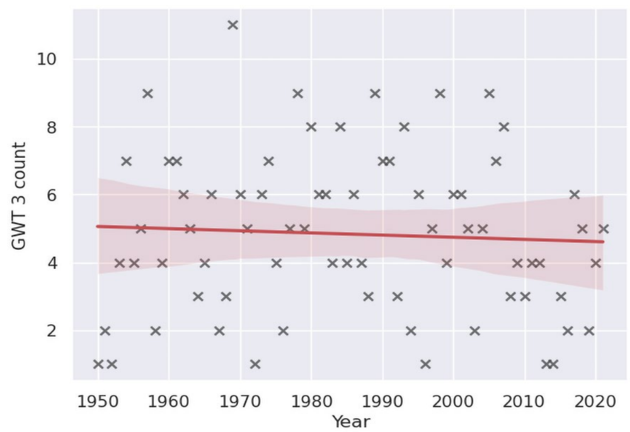

FIGURE 4: *GWT 3 counts per JJA season for each year. No significant trend can be seen from historical data, but there is a tendency for a decrease in the frequency of such circulation patterns. Note that this only depicts the dynamic component, i.e., circulation, that is associated to that event.*

CHARACTERISTICS OF EXTREME EVENTS IN THE PAST

DISTRIBUTION AND TRENDS OF EXTREME PRECIPITATION

The highest precipitation intensities in the pilot region are recorded in Wipptal (Pflersch station) and in the southern part of Stubaital in correspondence of the highest elevation locations (Dresdner Hütte station). In these areas, the annual maxima of 1-day precipitation (Rx1d) are in the range of 60-70 mm, and the annual sum of heavy 1-day precipitation (R97pTOT_1d) reaches 200 mm, as averages over the 1991–2020 period. On a seasonal basis, the highest 1-day precipitation intensities occur in summer and, secondarily in autumn, for all the analysed stations.

The trend analysis revealed an overall tendency towards more intense and frequent daily precipitation events. The 1-day precipitation maxima over 1980–2022 reported an increase in precipitation intensity both on a yearly basis and in the summer season for most stations, especially in the Wipptal area, while reductions are obtained for surrounding locations on the eastern side of the area. However, no trend is statistically significant (***FIGURE 5***). Similarly, the trends in the sum and frequency of daily precipitation extremes in summer and on a yearly basis are positive at almost all sites but not statistically significant (figure not shown).

If trends are computed over 1960–2022 for the longest station records (9), similar findings are obtained.

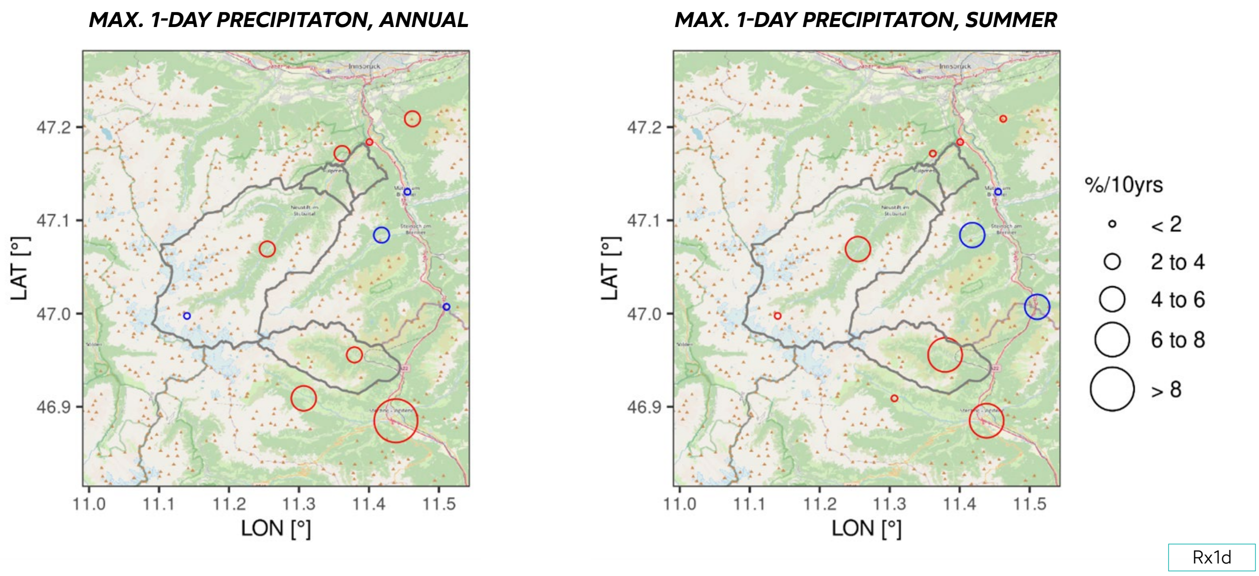

FIGURE 5: *Distribution of annual (left) and summer (right) trends over 1980–2022 for 1-day precipitation maxima (Rx1d) at station locations with at least 90 % of available data over the analysed period. Empty circles represent not significant trends. Trends are reported as percentage per decade with respect to the average values over 1991–2020.*

OCCURRENCE PROBABILITY OF THE EXTREME PRECIPITATION EVENTS

To evaluate the rarity and relevance of the extreme precipitation events of August 2021 and July 2022, the extreme values analysis was applied to the available station series of 1-day summer maxima (1980–2022) and the return levels associated to different return periods were calculated (***TABLE 2***).

As already observed from the spatial distribution of mean 1-day summer maxima, the sites in Wipptal report in general the highest return levels, up to almost 110 mm for a 100-y recurring event.

The precipitation event on 16th August 2021 in Wipptal reached ~ 50 mm in Fleres and 85 mm in Ladurno in one day. Based on the data for Fleres, the event has an estimated return period of less than five years. In Stubaital, the 1-day precipitation on 22nd July 2022 reached 70 mm in Neustift with an estimated return period of about 13 years. Even though the return periods associated to both episodes are not exceptionally long, the short-duration intensity of these rainfall events triggered impactful processes. For instance, most of 1-day precipitation totals on 16th August 2021 occurred in three hours, with almost 40 mm recorded in Fleres. Similarly, the precipitation event on 22nd July 2022 in Stubaital was concentrated in a few hours, with about 50 mm cumulated in three hours and 30 mm in one hour in Neustift. By considering the available sub-daily information for Fleres from 1995 to 2023, the 3-hour cumulated rainfall of the event is associated to a return period of five years. In Neustift the estimated return period of the 1-hour precipitation peak during the event is about 30 years, based on the available hourly records from 2004 to 2023.

TABLE 2: *Return levels of summer maxima of 1-day precipitation (mm) for different return periods calculated for each station over the period 1980–2022 using the Generalized Extreme Value distribution.*

RP (years)	**Pflersch** (IT)	**Ridnaun** (IT)	**Sterzing** (IT)	**Dresdner Huette** (AT)	**Brenner** (AT)	**Matrei** (AT)	**Neustift Volderau** (AT)	**Patscherkofel** (AT)	**Schoenberg** (AT)	**Telfes** (AT)	**Trins** (AT)
10	74.8	76.2	64.7	69.3	71.2	60.6	61.0	52.2	52.6	53.4	65.0
20	85.7	85.9	78.3	80.8	82.6	67.1	73.8	57.6	59.6	62.9	73.4
50	100.1	98.3	98.9	96.8	98.7	75.0	94.4	63.9	68.8	77.2	84.1
100	111.0	107.5	116.9	109.7	111.8	80.5	113.4	68.4	76.0	89.8	91.9

WHAT TO EXPECT IN THE FUTURE?

Projected changes in the intensity of heavy precipitation are investigated based on the annual maximum of precipitation (Rx1d). The changes are reported as the median of the changes calculated by the 5 available models under four levels of global warming (***FIGURE 6***). As average over the whole Wipptal/Stubaital area and as median of the model simulations, the annual maximum intensity of 1-day precipitation will increase between + 4 % (GWL1.5) and + 16 % (GWL4) in Wipptal, and between + 4 % (GWL2) and + 15 % (GWL4) in Stubaital with respect to the 1991–2020 conditions.

Similar increases are projected for the summer maximum of 1-day precipitation, with averages over the whole Wipptal and Stubaital area and median of the model simulations between + 4 % (GWL1.5) and + 9 % (GWL4) for Wipptal, and between + 5 % (GWL2) and + 17 % (GWL4) in Stubaital with respect to 1991–2020 conditions.

Projected changes in the frequency of heavy precipitation are investigated based on the annual number of exceedances of the 97th percentile (R97pN_1d). The changes are reported as the median of the changes

MAX. 1-DAY PRECIPITATION, ANNUAL

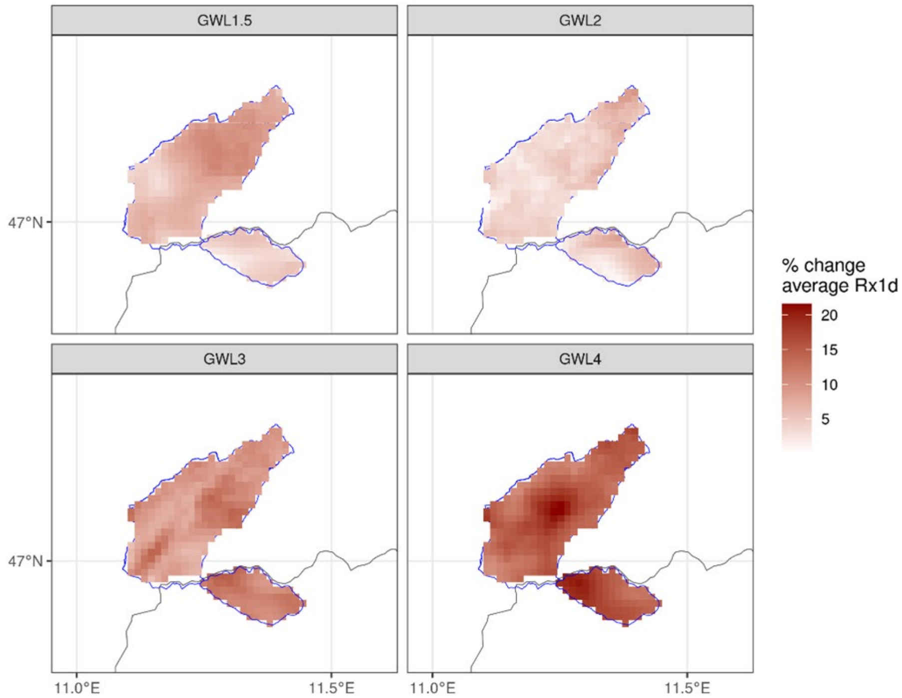

FIGURE 6: *Projected percentage changes in annual Rx1d under different future Global Warming Levels (GWLs) with respect to the baseline 1991–2020. The maps report the median of the models.*

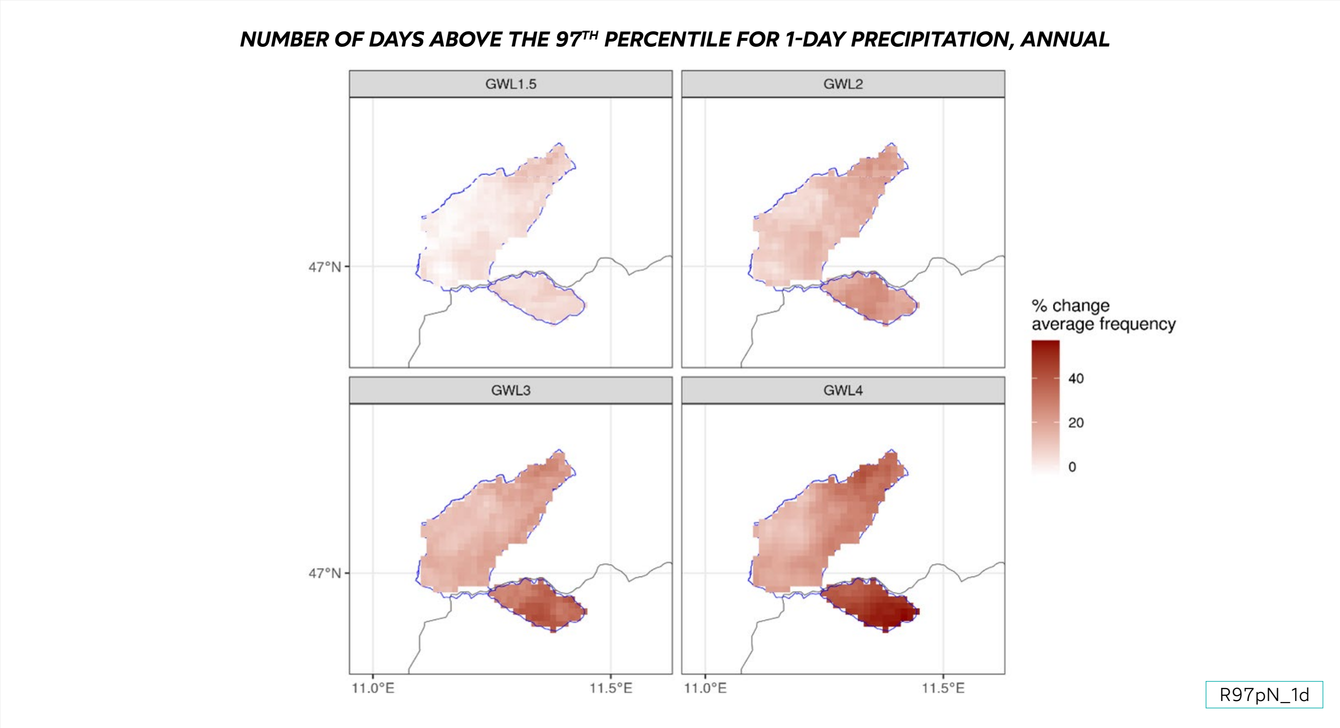

FIGURE 7: *Projected percentage changes in annual number of exceedence of 97th percentile of daily precipitation, under different future Global Warming Levels (GWLs) with respect to the baseline 1991–2020. The maps report the median of the models.*

calculated by the 5 available models under four levels of future global warming (***FIGURE 7***). As average over the whole Wipptal/Stubaital area and as median of the model simulations, the annual number of exceedances will increase between + 6 % (GWL1.5) and + 46 % (GWL4) in Wipptal, and between + 3 % (GWL2) and + 23 % (GWL4) in Stubaital with respect to the 1991–2020 conditions.

The frequency of heavy 1-day precipitation in summer is also projected to increase. The changes, as median of the models and average over each subregion, are up to + 22 % in Wipptal and + 14 % in Stubaital under GWL4 with respect to the 1991–2020 reference.

The projected changes in return levels of 1-day annual precipitation maxima corresponding to return periods of 10, 20, 50 and 100 years were calculated based on the five EURO-CORDEX projections and the four GWLs for Wipptal/Stubaital area. In particular, the projected changes are computed with respect to the 50-year baseline period 1971–2020 and reported as median of the model ensemble.

On a regional level, the projected changes in the return levels of 1-day precipitation extremes are positive for all return periods and under all GWLs, for both Stubaital and Wipptal areas (***TABLE 3***). In general, the relative increases are higher in Wipptal, especially for the return levels corresponding to the longest return periods. For a 100-year event, the projected increases of precipitation intensity are in the range of + 2 % (GWL2) and + 24 % (GWL4) for Stubaital, while for Wipptal they are between + 6 % (GWL1.5) and + 36 % (GWL4).

TABLE 3: *Mean projected percentage changes in return levels of annual Rx1d for the Stubaital/Wipptal areas based on the ensemble of the 5 adjusted EURO-CORDEX simulations under different GWLs with respect to the 50-year baseline 1971–2020. Values are reported as median of the model projections.*

% changes	GWL 1.5 °C	GWL 2 °C	GWL 3 °C	GWL 4 °C
10-y event	3.8 / 3.0	5.5 / 8.4	7.9 / 10.5	13.0 / 12.7
20-y event	5.1 / 3.9	5.3 / 8.2	9.9 / 11.8	15.3 / 18.1
50-y event	5.2 / 4.8	3.6 / 9.4	9.7 / 14.1	20.0 / 27.8
100-y event	3.8 / 6.0	1.7 / 12.1	9.2 / 17.3	23.6 / 36.2

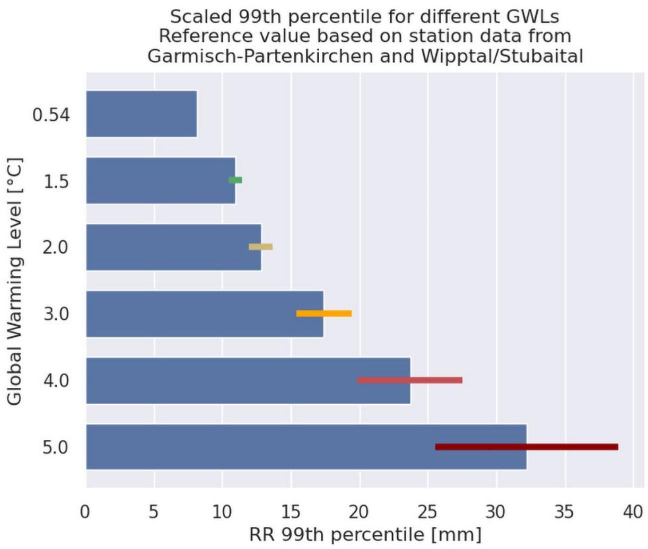

FIGURE 8: *Scaled 99th percentile of hourly precipitation rates for different GWLs. The first row depicts the current Warming Level according to the 30-year period 1991 to 2020.*

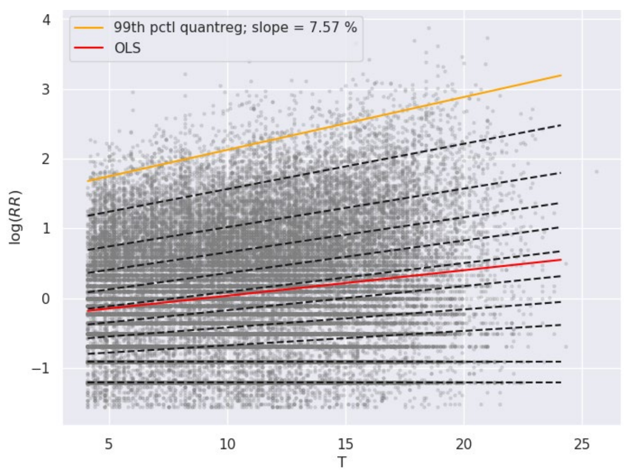

FIGURE 9: *Quantile and least squares regression for all station data for RR > 0.2 and T > 4 (these two filters reflect using only wet days and days outside winter). The regressed 99th percentile yields a slope of ~ 7.6 %, which is in rough agreement with Haslinger et al. (in prep.).*

R99pN_1h

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 (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 for all GWLs are shown in ***FIGURE 8***. It is evident (and follows from the definition of scaling), that the uncertainty grows with higher GWLs. All station data located in the pilot areas of Wipptal/Stubaital and Garmisch-Partenkirchen (DE) 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.

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 also 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 Pathways) 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.

Projected changes are calculated for all model simulations and reported in terms of ensemble model median.

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; 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 · 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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