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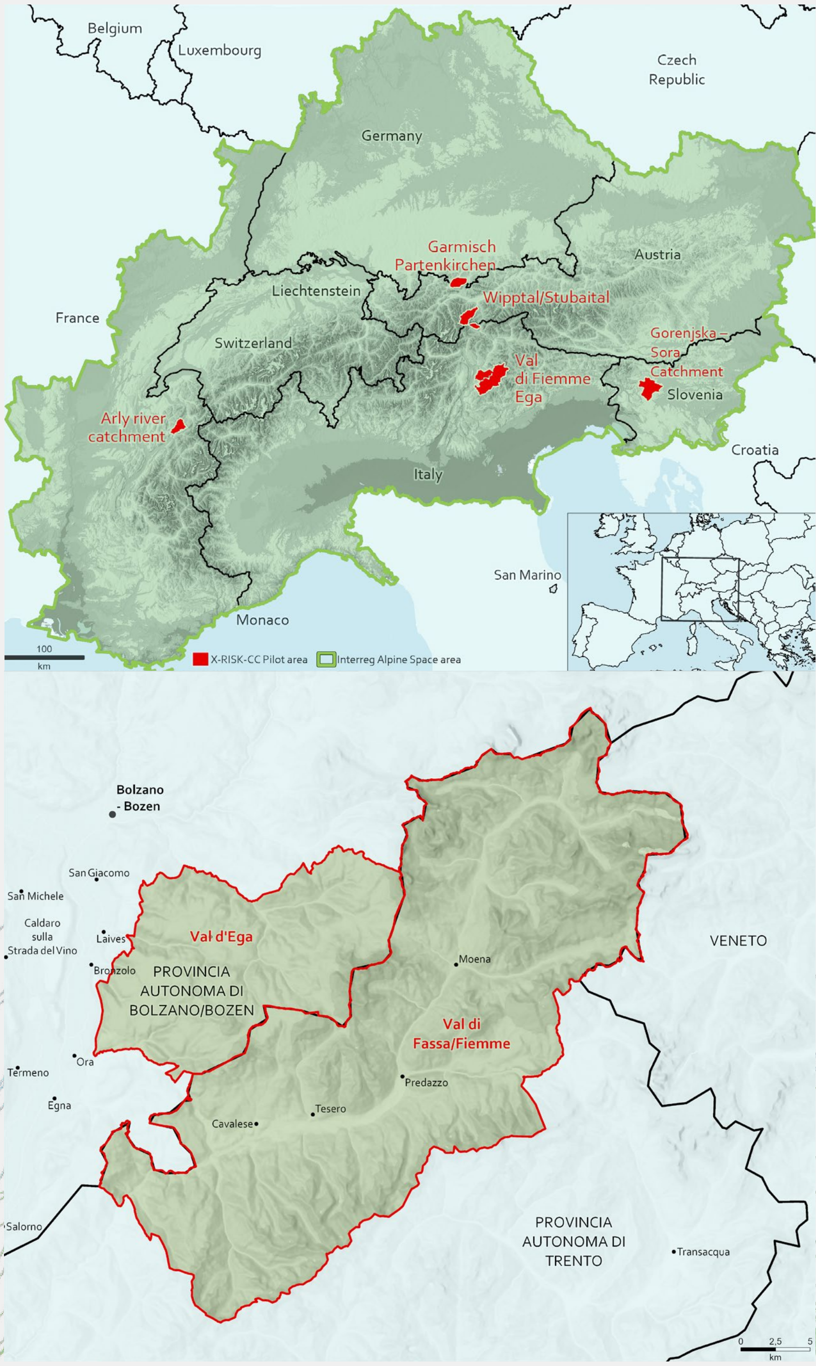

X-RISK-CC pilot areas (top) and the pilot area of the Vaia storm (bottom)

THE VAIA STORM IN THE EASTERN ALPS – THE CASE OF TRENTINO – SOUTH TYROL (FASSA/FIEMME AND CAREZZA/EGA VALLEYS)

Italy

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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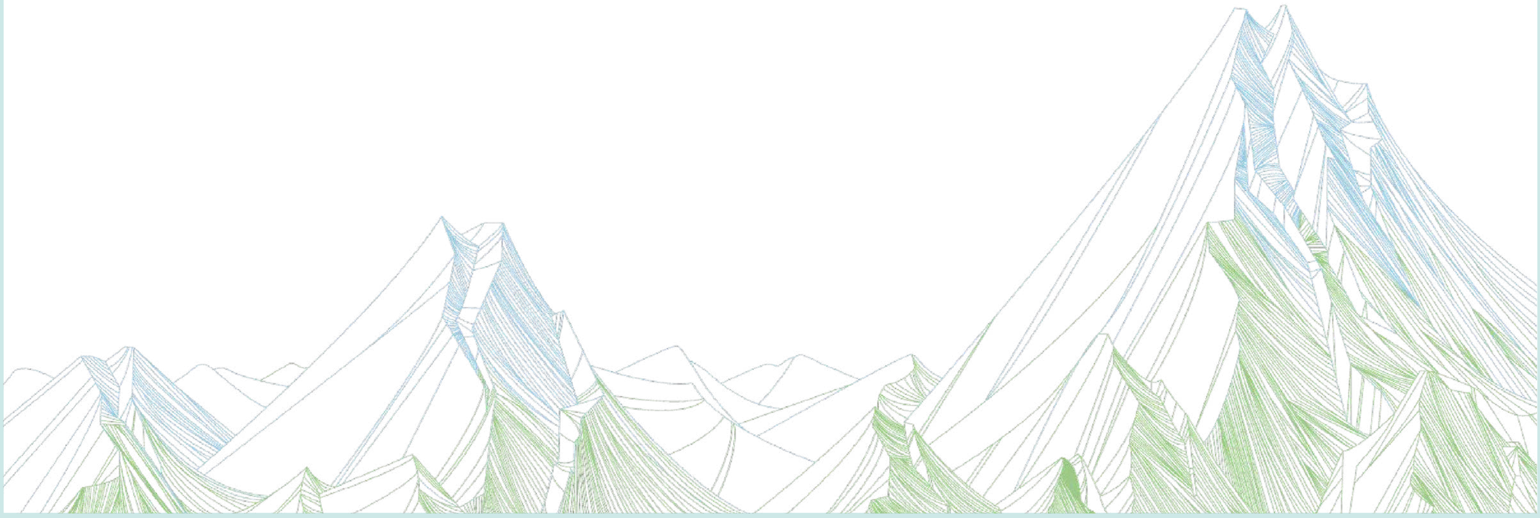


KEY MESSAGES

- The intensity of heavy 1-day precipitation increased in Trentino – South Tyrol from 1956 to 2020, especially in the northern part of South Tyrol, where the trends are statistically significant. The most pronounced increases in rainfall intensity occurred during the summer and autumn seasons.

- Compound extreme precipitation and wind events occurred more frequently in autumn and summer. No clear spatial patterns are observed, but the distribution of areas mostly affected by compound wind speed and precipitation extremes depends on the season. However, the number of summer and autumn events recorded in 1991–2020 is particularly high in the area including or close to the pilot area of Fassa/Fiemme and Carezza/Ega Valleys.

- The Vaia storm was recorded as one of the most exceptional compound events of the last 30 years and particularly intense in the eastern portion of the region including Fassa/Fiemme and Carezza/Ega Valleys. In this portion of the region, the return periods associated with the accumulated precipitation exceeded 100 years.

- The frequency of the circulation types associated with the Vaia storm shows a substantial increase over the last 70 years. Moreover, based on weather station records, a precipitation event like Vaia is found to be more probable in more recent decades with respect to the past.

- In the future, the intensity and frequency of daily precipitation extremes are projected to increase throughout Trentino – South Tyrol. On average, the intensity of annual maxima of daily precipitation is expected to increase by + 16 % with respect to current conditions under the worst scenario, i.e. considering a global warming level of + 4 °C (GWL4). Also, a Vaia-like precipitation event is expected to become more probable in the future: its return period is expected to be halved with respect to 1981–2020 under a global warming scenario equal or more than + 3 °C.

- The projected increase in heavy precipitation intensity and frequency is expected to drive a rise also in compound extreme precipitation and wind events in the region, especially under the warmest scenarios. With a future global warming of + 4 °C, the frequency of these events is projected to increase by 18 % compared to current conditions (1991–2020).

PAST EXTREME EVENTS IN FOCUS

LARGE-SCALE STORM IN OCTOBER 2018 WITH EXTREME PRECIPITATION AND WIND SPEED LEADING TO FOREST DAMAGES, FLOODS AND GRAVITATIONAL MASS MOVEMENTS IN THE EASTERN ALPS

Between 27th and 30th October 2018 an exceptional Mediterranean storm named Vaia hit the eastern Alps leading to severe damages in many Alpine regions. Due to the combination of intense precipitation and extremely high wind speed, several windfalls, floods and debris flows were recorded in the Italian Trentino – South Tyrol region, especially in the pilot area centred on the Fiemme and Ega Valleys where the huge number of fallen trees modified the forest landscape substantially. During the first three days of the event, most observation sites in South Tyrol and Trentino registered record values of cumulated precipitation, in some cases exceeding 400 and even 600 mm in a few locations in Trentino (Passo Cereda and Passo Pian delle Fugazze). On 29th October, exceptional wind speeds occurred in combination with rainfall, with the highest values observed between 1,500 and 2,000 m above sea level (a.s.l.) where wind gusts exceeding 120 km/h were recorded.

FIGURE 1: *Windthrown trees after the Vaia storm in the area of Karerpass in South Tyrol (Source: Civil Protection Agency of the Province of Bolzano).*

DEFINITION OF METEOROLOGICAL EXTREMES

EXTREME PRECIPITATION

Rx1d, Rx3d, Rx5d: annual and seasonal precipitation maxima over 1 day, 3 days and 5 days.

R97pTOT_1d: annual and seasonal 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 seasonal number of days with precipitation exceeding the 97th percentile computed over the reference period (1991–2020) considering only wet days (daily precipitation ≥ 1 mm).

EXTREME WIND SPEED

WSx1d: annual and seasonal maxima of daily wind speed maximum. Daily wind speed maximum is defined as the maximum of 10-min averages.

WS97pN_1d: annual and seasonal number of days with daily wind speed maximum exceeding the 97th percentile of the reference period 1991–2020.

COMPOUND EXTREME PRECIPITATION AND WIND SPEED

RWSx_3d: product of two standardized values (based on reanalysis data): (1) the accumulated precipitation over 3 days, and (2) the maximum 1-day wind speed recorded on the same 3 days window. Both values are standardized using the annual or seasonal averages and standard deviations from the reference period 1991–2020.

RWS97pN_3d: annual and seasonal number of days with both 1-day wind speed maximum and 3-day precipitation above the 97th percentile for the reference period 1991–2020 (based on reanalysis data).

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

	Global Climate Model	**Regional Climate Model** (Institute)
1	CNRM-CM5	CCLM4-8-17 (CLMcom)
2	CNRM-CM5	COSMO-crCLIM-v1-1 (CLMcom-ETH)
3	CNRM-CM5	ALADIN63 (CNRM)
4	CNRM-CM5	RACMO22E (KNMI)
5	CNRM-CM5	ALARO-0 (RMIB-Ugent)
6	EC-EARTH	CCLM4-8-17 (CLMcom)
7	EC-EARTH	COSMO-crCLIM-v1-1 (CLMcom-ETH)
8	EC-EARTH	RegCM4-6 (ICTP)
9	EC-EARTH	WRF381P (IPSL)
10	EC-EARTH	RACMO22E (KNMI)
11	IPSL-CM5A-MR	WRF381P (IPSL)
12	HadGEM2-ES	CCLM4-8-17 (CLMcom)
13	HadGEM2-ES	RACMO22E (KNMI)
14	MPI-ESM-LR	CCLM4-8-17 (CLMcom)
15	MPI-ESM-LR	COSMO-crCLIM-v1-1 (CLMcom-ETH)
16	MPI-ESM-LR	REMO2009 (MPI-CSC)

DATA

For the pilot area analyses, we used quality-checked observations of daily precipitation for 67 station locations in Trentino – South Tyrol and surrounding areas. Since the time series have different temporal extents, the analysis period considered in the following is 1956–2020. All selected station series are almost complete over the considered interval (a station series is considered complete if it has less than six years with more than 15 % of missing data). Wind speed data are available for 63 stations, but most series are very short and only 9 series cover a 20-year period, since 2003. The limited spatial and temporal coverage of maximum wind speed observations prevents a robust analysis of wind and compound extremes: therefore, the CERRA reanalysis (Copernicus European Regional ReAnalysis) was used to supplement the analysis (~ 5 km resolution).

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 and snowfall.

Future analyses of precipitation extremes are based on the daily EURO-CORDEX projections adjusted on observations and available on a 1-km grid covering Trentino – South Tyrol (***TABLE 1***), while daily maximum wind speed projections are derived from the original EURO-CORDEX simulations at about 12 km (***TABLE 2***). For the assessment of compound conditions, the original EURO-CORDEX simulations for both variables were used to ensure consistency.

It is important to note that station observations and model simulations, especially future projections, are not directly comparable, even after the bias-adjustment procedure, due to the differences in the spatial scales resolved. The coarser spatial resolution of the model simulations limits the representation of local-scale features, especially in orographically-complex regions.

TABLE 2: *List of EURO-CORDEX models used for the evaluation of projected changes of wind and compound extremes in Trentino – South Tyrol. All simulations were used at the original spatial resolution (~ 12 km) without bias adjustments.*

	Global Climate Model	**Regional Climate Model** (Institute)
1	CNRM-CM5	COSMO-crCLIM-v1-1 (CLMcom-ETH)
2	EC-EARTH	COSMO-crCLIM-v1-1 (CLMcom-ETH)
3	EC-EARTH	COSMO-crCLIM-v1-1 (CLMcom-ETH)
4	HadGEM2-ES	COSMO-crCLIM-v1-1 (CLMcom-ETH)
5	MPI-ESM-LR	COSMO-crCLIM-v1-1 (CLMcom-ETH)
6	MPI-ESM-LR	COSMO-crCLIM-v1-1 (CLMcom-ETH)
7	MPI-ESM-LR	COSMO-crCLIM-v1-1 (CLMcom-ETH)
8	NorESM1-M	COSMO-crCLIM-v1-1 (CLMcom-ETH)
9	CNRM-CM5	RCA4 (SMHI)
10	EC-EARTH	RCA4 (SMHI)
11	EC-EARTH	RCA4 (SMHI)
12	HadGEM2-ES	RCA4 (SMHI)
13	MPI-ESM-LR	RCA4 (SMHI)
14	MPI-ESM-LR	RCA4 (SMHI)
15	MPI-ESM-LR	RCA4 (SMHI)
16	IPSL-CM5A-MR	RCA4 (SMHI)
17	NorESM1-M	RCA4 (SMHI)

TYPICAL SYNOPTIC SITUATION LEADING TO THE EXTREME EVENT

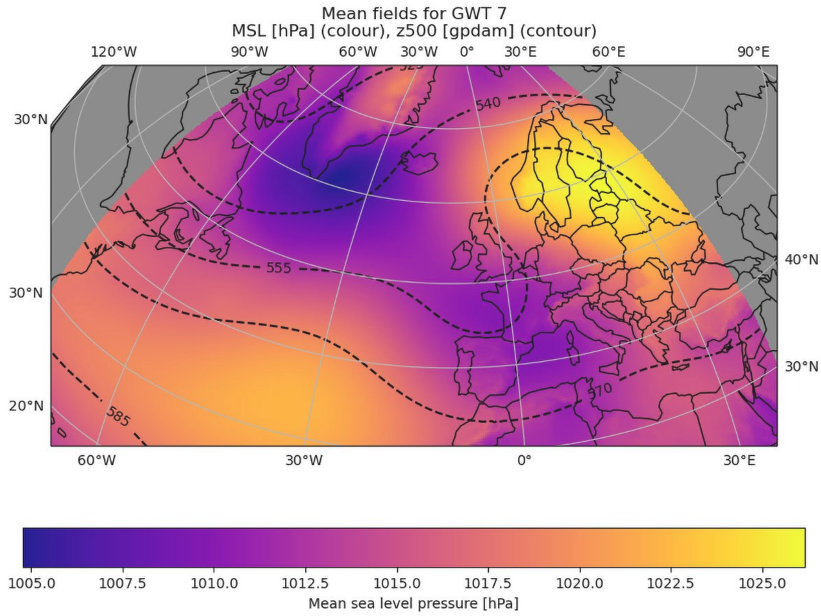


FIGURE 2: *Prevailing GWT (Gross Wetter Type) for Vaia: GWT 7. Mean sea level pressure is shown in colors, 500 hPa geopotential as contours.*

The prevailing circulation type for Vaia is GWT 7 ('Gross-Wetter-Type'; a circulation type classification), which can be seen in ***FIGURE 2***. The large-scale circulation is governed by a low-pressure system over Western Europe and a blocking high-pressure system over Scandinavia. The corresponding through over Western Europe reaches south, over France and Spain, into the Mediterranean Sea. This causes Southerlies in the Alpine region and precipitation south of the Alpine ridge. Furthermore, the geopotential height ridge over Eastern Europe blocks atmospheric flow and can hence be a reason for long-lasting precipitation. As visible in ***FIGURE 3***, this large-scale circulation pattern and the corresponding southerly flow in the Alpine region was stationary for a few days, which led to continuous precipitation. Using consecutive 2-day GWT 7 patterns during autumn (September to November, SON) as indicator for such an event, ***FIGURE 4*** shows a substantial increase in frequency over the observational period. Across 70 years, this indicates roughly a doubling of such 2-day events, which are characterized by stationary southerly flow.

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.

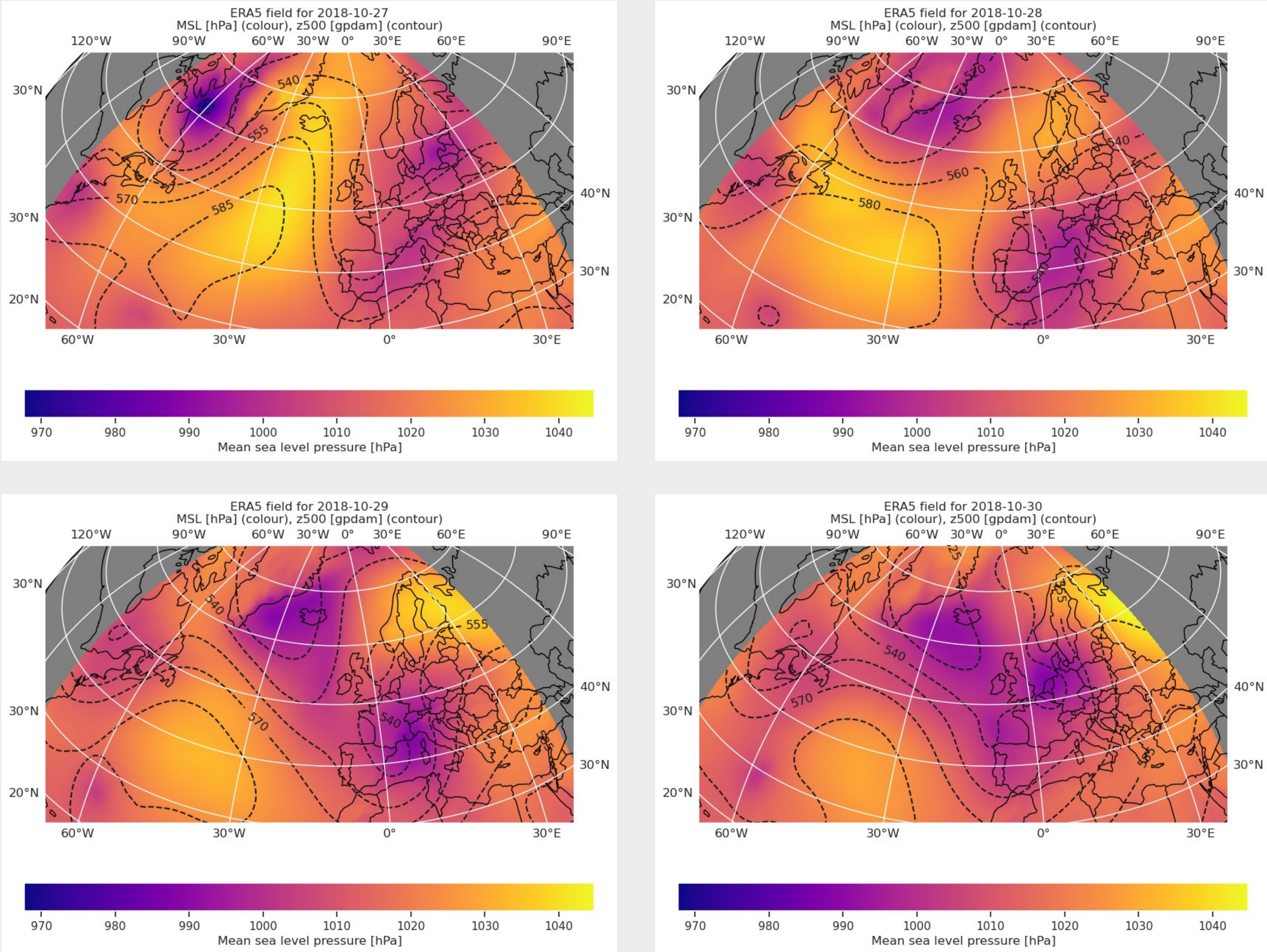


FIGURE 3: *Mean sea level pressure and geopotential height in 500 hPa for the Vaia event based on ERA5 reanalysis data. Mean sea level pressure is shown in colors, 500 hPa geopotential as contours.*

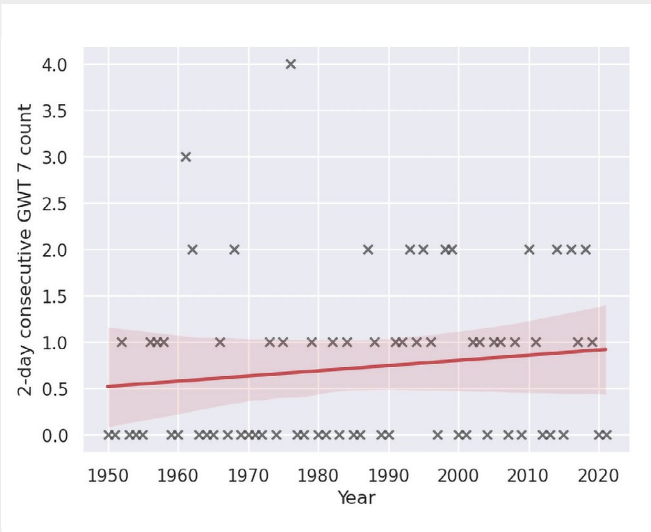


FIGURE 4: *2-day consecutive GWT 7 counts per autumn (SON) for each year. A significant trend can be seen from historical data. Note that this only depicts the dynamic component, i.e. circulation, that is associated with that event.*

CHARACTERISTICS OF EXTREME EVENTS IN THE PAST

DISTRIBUTION AND TRENDS OF EXTREME PRECIPITATION

The annual indices for intensity of heavy precipitation exhibit distinctive spatial patterns in both magnitude and seasonality (***FIGURE 5***, left). Trentino (southern province of the region) and the central part of South Tyrol (northern province) stand out with the highest annual maxima of 1-day precipitation (Rx1d). Trentino registers more heavy precipitation events during autumn (September to November, SON), probably due to a higher exposure to moist air masses from the Mediterranean Sea, while in South Tyrol precipitation maxima are more frequent in summer (from June to August, JJA), when more convective processes occur and are particularly influenced by orographic effects. Distinct spatial patterns are also exhibited by the frequency of daily precipitation above the 97th percentile (R97pN_1d), being the highest in South Tyrol during the summer season (figure not shown).

The spatial distribution of extreme precipitation intensity trends shows marked differences between southern and northern parts of the region (***FIGURE 5***, right). Results are here discussed for 1-day maxima, but comparable findings are obtained for 3- (Rx3d) and 5-day (Rx5d) precipitation maxima. The trend analysis for annual maxima reports an overall increasing tendency in the intensity of heavy precipitation throughout the region, with nearly two thirds of stations depicting a positive

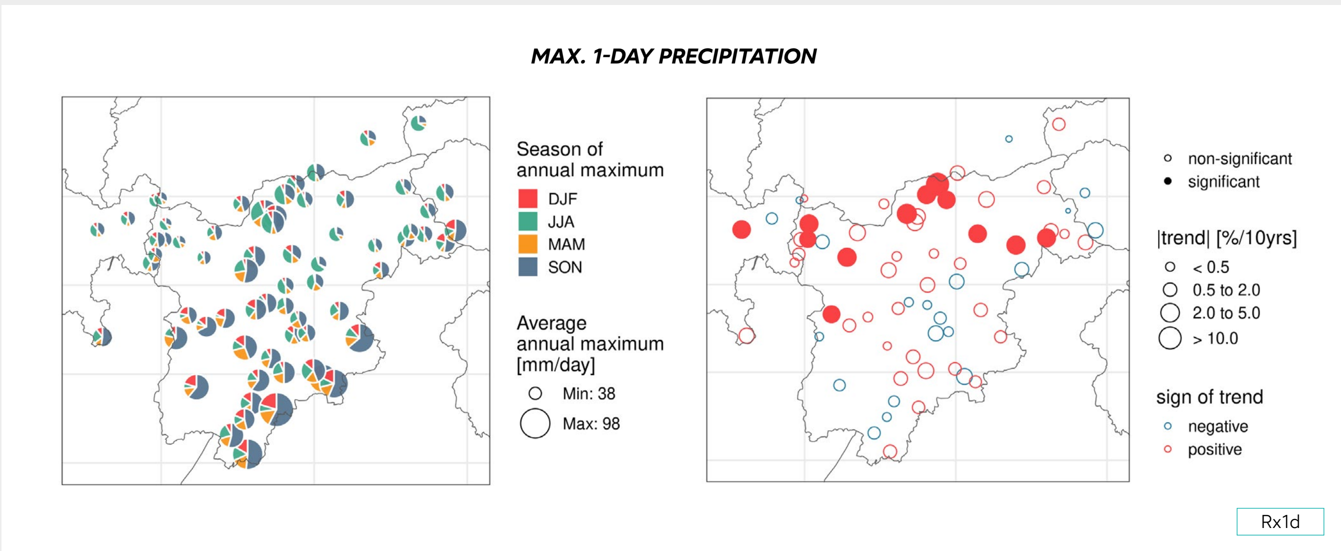


FIGURE 5: *Left: Spatial distribution of intensity and seasonality of Rx1d with point size depicting the average intensity and pie chart indicating the proportion of occurrence of the precipitation maxima over the seasons. Right: Spatial distribution of the magnitude and significance of trends (1956–2020) with point size indicating absolute trend magnitude, color distinguishing between positive (red) and negative (blue) trends and significant trends indicated by full circles. The trend values are expressed as % of change per decade with respect to Rx1d average over 1991–2020.*

trend over 1956–2020. The number of statistically significant trends is limited (less than 20 % of stations for trends in annual Rx1d) and confined spatially in South Tyrol with increases in 1-day annual maxima as high as + 7.7 % per decade (with respect to the average of Rx1d over the reference period 1991–2020). It is worth noting that all significant trends are positive.

The seasonal trend analysis indicates a more pronounced rise in the intensity of 1-day precipitation maxima in summer and autumn (***TABLE 3***), with significant increasing trends observed in both seasons especially in the northern part of South Tyrol (figure not shown).

The observed trends in the frequency of heavy 1-day precipitation are much less pronounced than trends in intensity, although there are some localized areas showing positive trends, with increases in the number of heavy precipitation days in a year in the order of + 10 % per decade. The frequency of seasonal precipitation extremes does not show significant changes in the region.

TABLE 3: *Summary table for observed trends in annual and seasonal maxima of 1-day precipitation (Rx1d). Values of trends are reported as percentage changes to the average of Rx1d over reference period (1991–2020). The reported range extends from the minimum to the maximum trend values over all stations.*

	Trends in 1-day precipitation maxima (Rx1d)		
	Mean [%/decade]	**Range** [%/decade]	**% significant trends**
year	1.4	(-3.2 ; 7.7)	18.2
winter	0.2	(-9.3 ; 6.2)	3.0
spring	0.0	(-7.1 ; 4.6)	3.0
summer	1.1	(-3.4 ; 6.4)	16.7
autumn	1.3	(-5.8 ; 8.3)	10.6

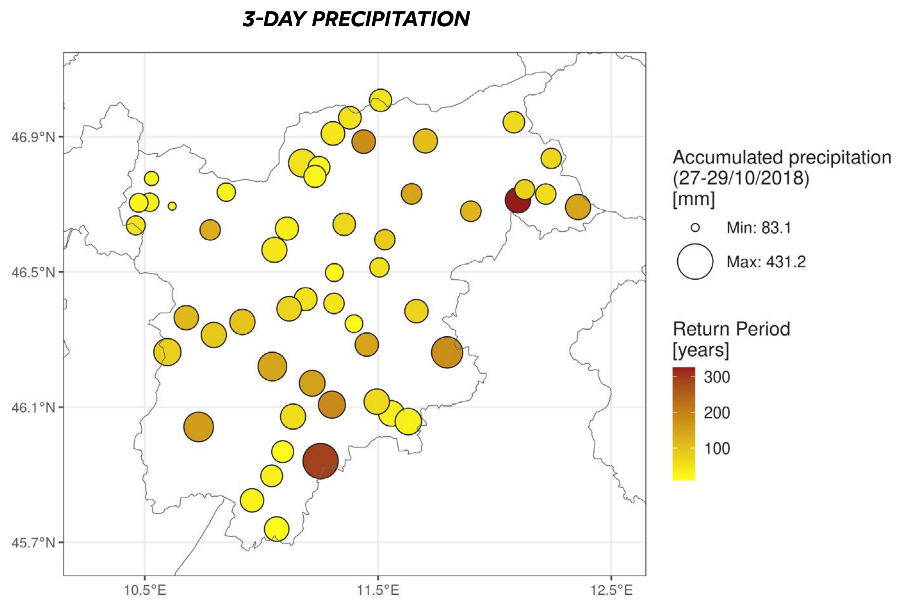


FIGURE 6: *Cumulated values and return periods of 3-day precipitation on 27th–29th October 2018 at station sites in Trentino-South Tyrol. The color scale represents the return periods while the size of points represents the precipitation amounts.*

REGIONAL FREQUENCY ANALYSIS AND RECURRENCE INTERVALS OF VAIA STORM

The statistical characteristics of the Vaia storm for Trentino – South Tyrol in terms of recurrence interval are investigated by means of the Regional Frequency Analysis (RFA). RFA is expected to reduce result uncertainty by pooling the data from multiple sites sharing comparable statistical characteristics. A cluster analysis based on local mean climate features is applied to identify such homogeneous groups of stations (more details are reported in the Methodology section). RFA is applied to assess the recurrence intervals of the Vaia event in terms of 3-day precipitation totals at station level, considering the 1956–2020 precipitation series of the 55 stations located in Trentino – South Tyrol and the five homogeneous sub-regions identified. The return periods estimated for the precipitation totals from 27th to 29th October during the Vaia storm are shown in ***FIGURE 6***. The return periods exceed 100 years in most of the region, with the highest values in the southern part (Trentino) and in the eastern part of the region, while shorter return periods are registered in the north-western portion (Venosta Valley). It is worth noting that when RFA is conducted on two subsequent 30-year periods (1956–1985 and 1991–2020), separately, the estimated return periods for the 3-day precipitation totals of the Vaia storm remarkably decrease for the most recent interval throughout the region up to - 95 %, the only exception occurring in the north-western region where the change is negligible (figure not shown). This suggests that Vaia-like events have become more frequent, and it remarks upon extreme value analysis being highly sensitive to input data, necessitating cautious interpretation of these results. It is also important to consider that, due to the limited size of the observation sample, the uncertainty associated with the RFA results related to the longest return periods, should be considered cautiously and interpreted as a general indication of the level of rarity of the event intensity.

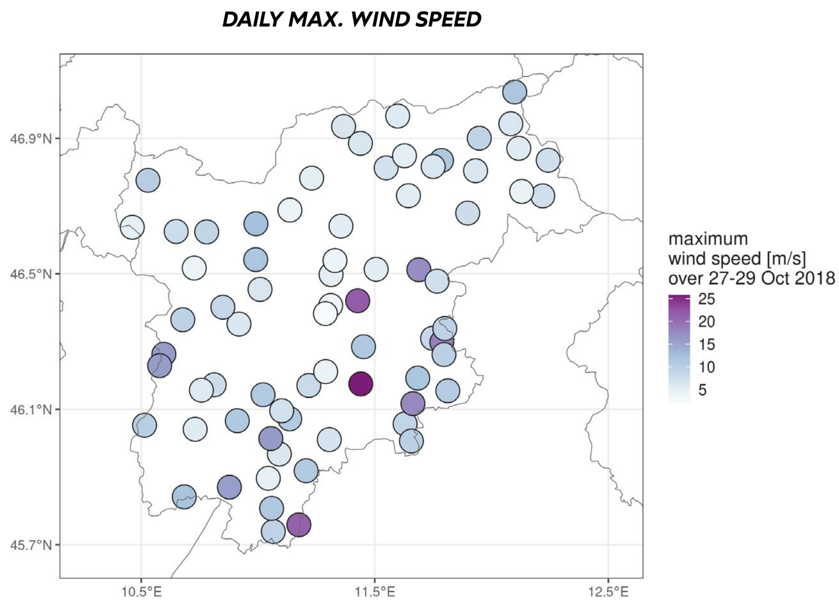


FIGURE 7: *Maximum wind speed over 27th–29th October 2018 at station sites in Trentino – South Tyrol.*

The short length of the available observation series (10–20 years) does not allow a similar analysis for maximum wind speed. However, the spatial variability of strong wind intensities was assessed based on the CERRA reanalysis data. The average annual maxima of daily maximum wind speeds (WSx1d) over the 1991–2020 period is approximately 9 m/s, as average over the region, with the highest values occurring in high-altitude areas. The observed spatial patterns of maximum wind speed occurred during the Vaia storm were assessed by visualizing the recorded values at all available station locations (***FIGURE 7***). It is worth noting that in several cases the wind speed maxima of the Vaia event correspond or are close to the maximum values of the entire station record. The highest values of wind speed occurred in Trentino, particularly in areas where also the highest values of accumulated precipitation were recorded. Since the daily maximum values are derived as the daily maxima over 10-minute average wind speed observations for the day, the reported values are lower than wind gusts recorded during the Vaia storm, which exceeded 120 km/h (~ 33 m/s) on 29th October 2018 at some stations.

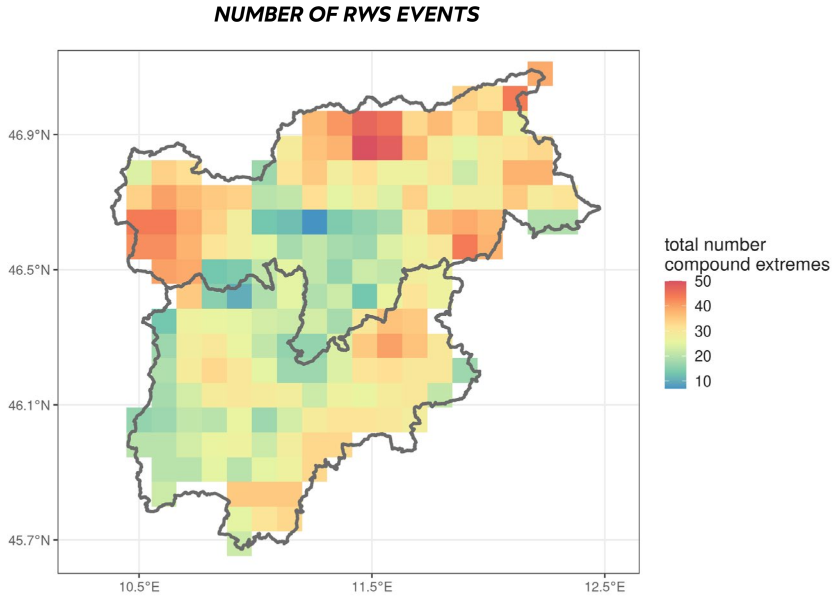


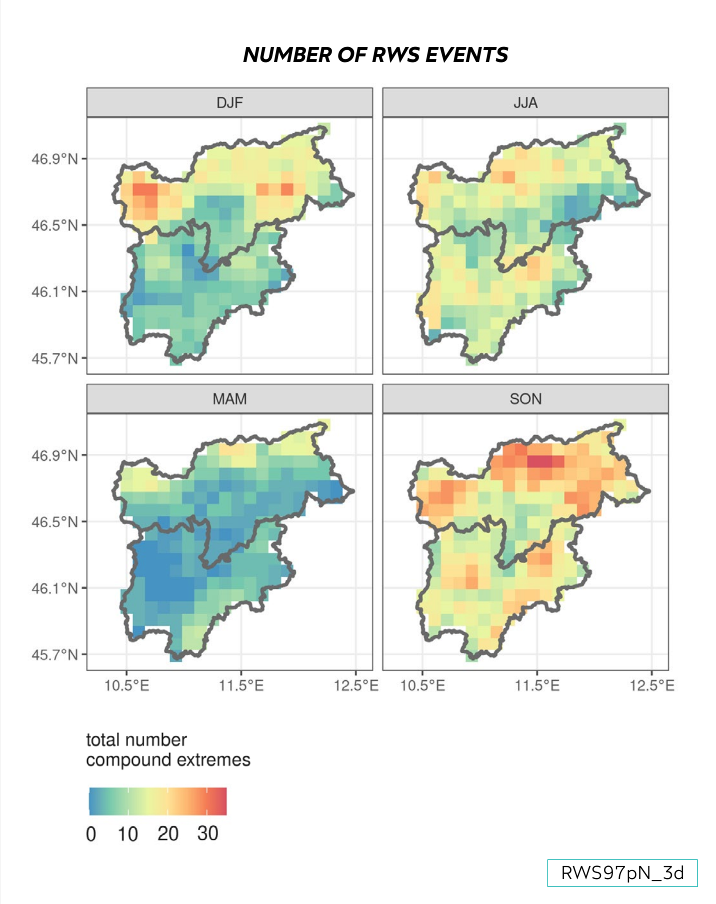
FIGURE 8: *Total number of compound precipitation and wind extremes during 1991–2020, as identified based on CERRA reanalysis.*

COMPOUND EXTREME EVENTS

As detailed in the Methods section, a compound extreme event is identified when both precipitation and wind speed exceed the corresponding 97th percentile (RWS97pN_3d).

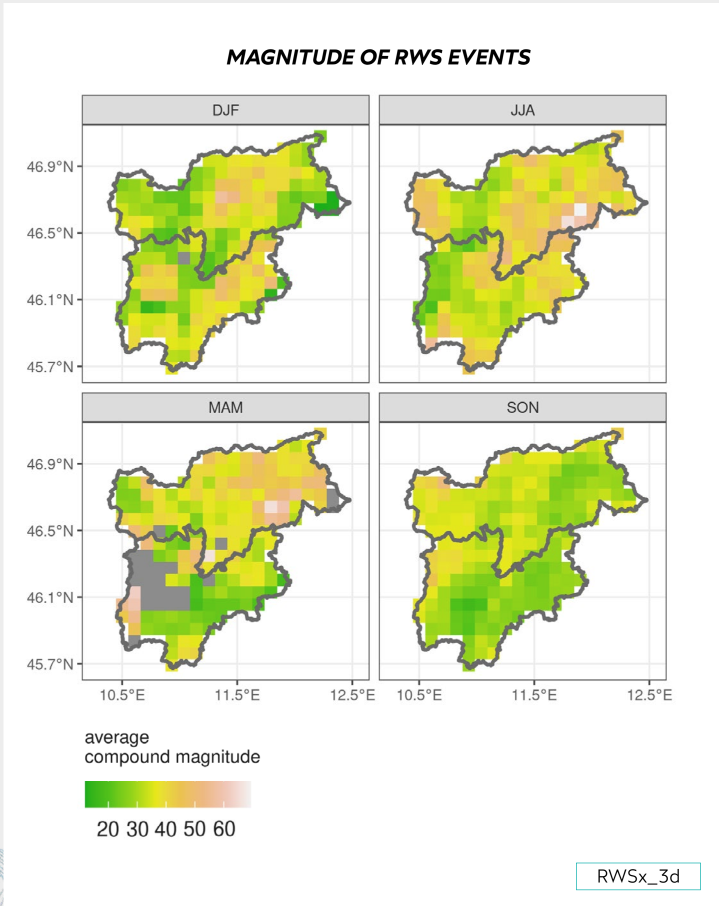
Based on the 9 available observation series covering 2003 to 2020, a larger number of compound extreme events occurred in the northern part of the region, with around 20 identified events over the period. In contrast, fewer than 10 compound events are registered by the station locations in Trentino. However, the very low spatial coverage of long wind speed observations limits the possibility to derive a comprehensive analysis of the spatial distribution of mean compound conditions over the region.

Using CERRA reanalysis data, a more comprehensive analysis of compound extreme events at the regional scale was performed. The reanalysis over a longer analysis period (1991–2020) confirms an overall higher occurrence of compound extremes in the northern part of the region, with up to 50 events compared to the regional average of 30 events. The continuous spatial extent of the CERRA reanalysis provides a more detailed description of the areas where past compound wind and precipitation extremes were more frequent (***FIGURE 8***). Specifically, these include the western part of South Tyrol (up to 50 events), the southeastern part of Trentino (up to 40 events), and the northeastern part of South Tyrol (up to 50 events).



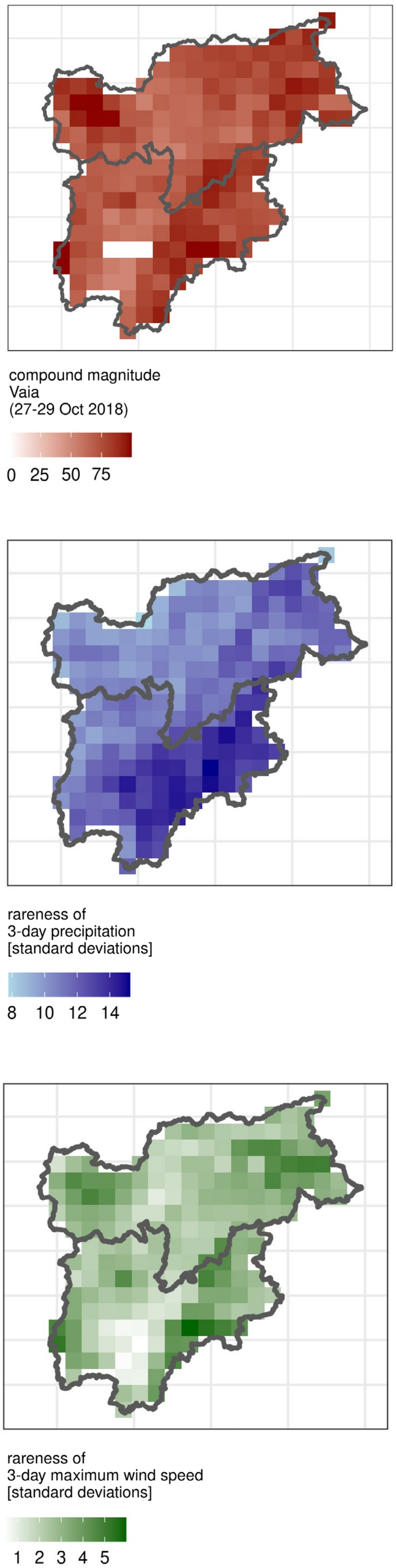
Compound extreme events of precipitation and wind occur more frequently in autumn (September to November, SON) and summer (June to August, JJA) on the whole region, while during winter (December to February, DJF) the frequency is higher in the northern part of the region (***FIGURE 9***). The lowest frequency of compound events is observed in spring (March to May, MAM) throughout the region.

FIGURE 9: *Total number of seasonal compound precipitation and wind extremes (RWS97pN_3d) during 1991–2020, as identified based on the CERRA reanalysis.*



The metric used to measure the magnitude of compound events (RWSx_3d) describes how extreme a compound event is relative to the local climatological conditions (as described by mean and standard deviation, on a yearly or seasonal basis), rather than indicating its absolute intensity. In other words, each event is compared to what is typical for that location, so that an intense (e.g., recording high value of precipitation) event might be "exceptional" in one season but might not be so remarkable in another. Seasonal analysis of the event magnitude (***FIGURE 10***) reveals that the highest magnitude relative to local conditions is exhibited by the compound events which occurred during summer (JJA). On a regional scale, autumn (SON) is the season with the lowest average magnitude of compound extremes involving precipitation and wind.

FIGURE 10: *Average compound magnitude (RWSx_3d) of seasonal extreme precipitation and wind events between 1991 and 2020, as identified using the CERRA reanalysis. Cells in grey did not record any compound extreme event in the corresponding season.*



Based on both observations and the CERRA reanalysis, the Vaia storm (i.e., precipitation accumulated on 27th–29th October 2018 and daily maximum wind speed over the same 3 days) was the most extreme regional compound event in Trentino – South Tyrol over the respective periods covered by data. 97 % of cells recorded a compound extreme, although the spatial variability of magnitude is high, especially in the eastern part of Trentino. The values of precipitation and wind speed recorded during the Vaia storm are exceptional also when compared to typical precipitation and wind values for the region in SON (***FIGURE 11*** top). The accumulated precipitation during the Vaia storm contributed much more to the exceptionality of the event than daily maximum wind speed (***FIGURE 11*** middle and bottom).

FIGURE 11: *Top: Spatial distribution of compound magnitude (RWSx_3d) associated with compound precipitation and wind speed on 27th–29th October 2018. Middle: Rareness of 3-day precipitation of the Vaia event expressed in terms of standard deviations based on values of 3-day precipitation during autumn. Bottom: Rareness of maximum wind speed during the Vaia event expressed in terms of standard deviations based on values of maximum daily wind speed in autumn.*

WHAT TO EXPECT IN THE FUTURE?

Annual maxima of 1-day precipitation (Rx1d) are projected to increase in the pilot area in the future under all Global Warming Levels (GWLs) considered (+ 1.5 °C, + 2 °C, + 3 °C and + 4 °C; see ***FIGURE 12***). The median of all model simulations reports an average increase of precipitation intensity over the pilot area between + 3 % (GWL1.5) and + 16 % (GWL4) with respect to 1991–2020.

The projected total intensity of daily precipitation extremes (R97pTOT_1d) also significantly increase in the region: the median of all model simulations reports an average increase over the pilot area between + 8 % (GWL1.5) and + 51 % (GWL4) with respect to 1991–2020.

In addition, the return periods of a Vaia-like precipitation event in the future are also investigated by extracting the precipitation projection at each station location and applying the Regional Frequency Analysis (RFA) to 3-day precipitation annual maxima. About 90 % (GWL3 and GWL4) of stations report a reduction (as model median) of the return periods associated to a Vaia-like precipitation event by more than 50 % with respect to 1981–2020, while more limited changes are

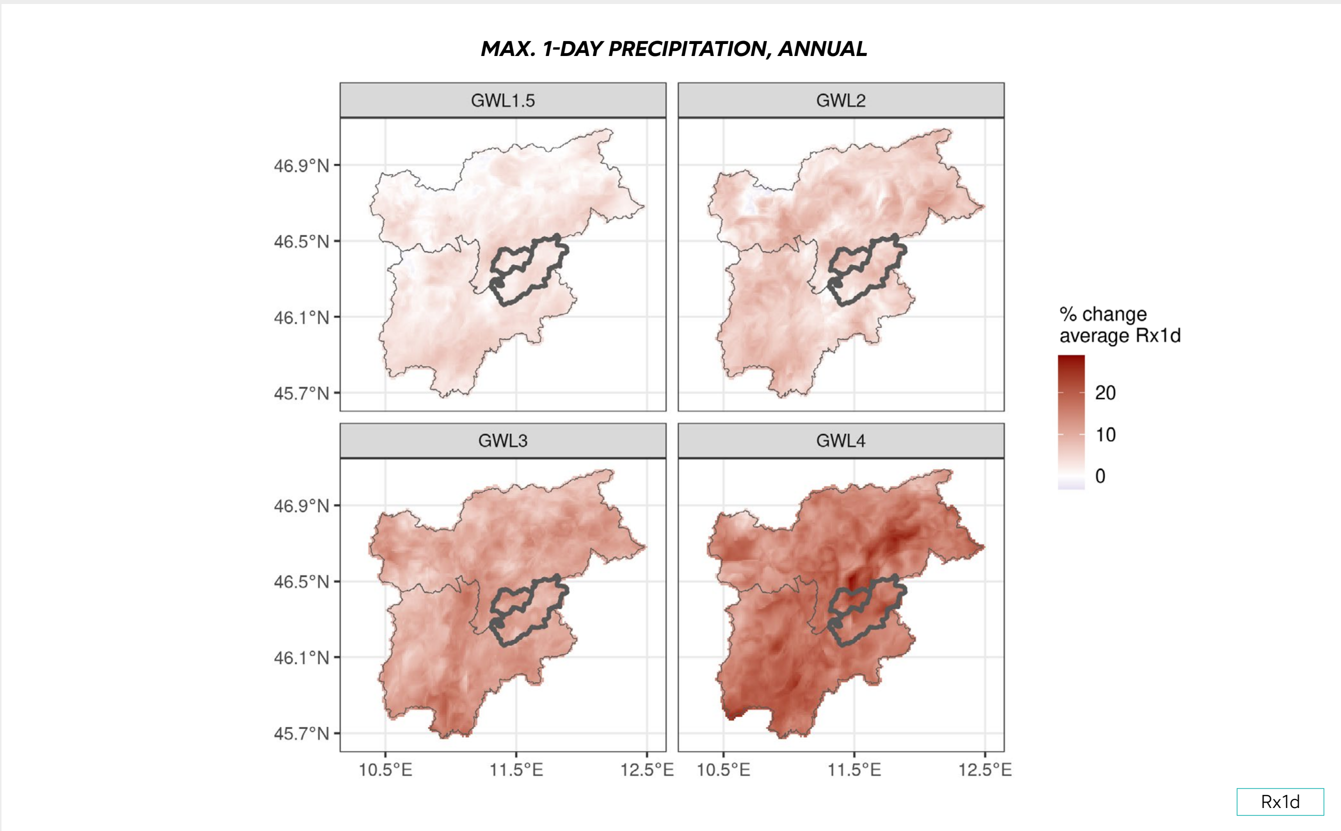
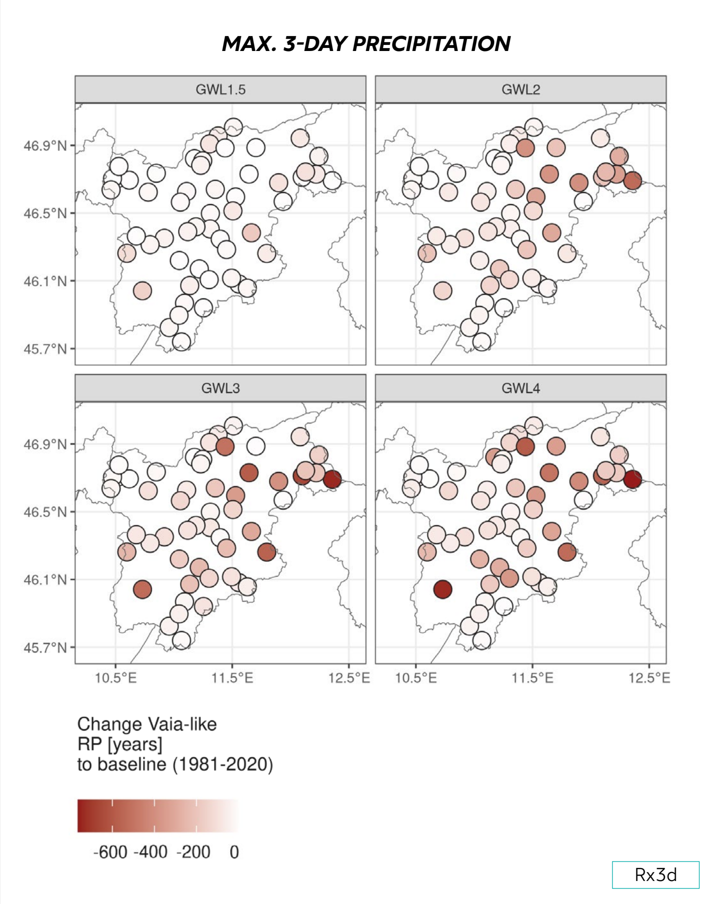


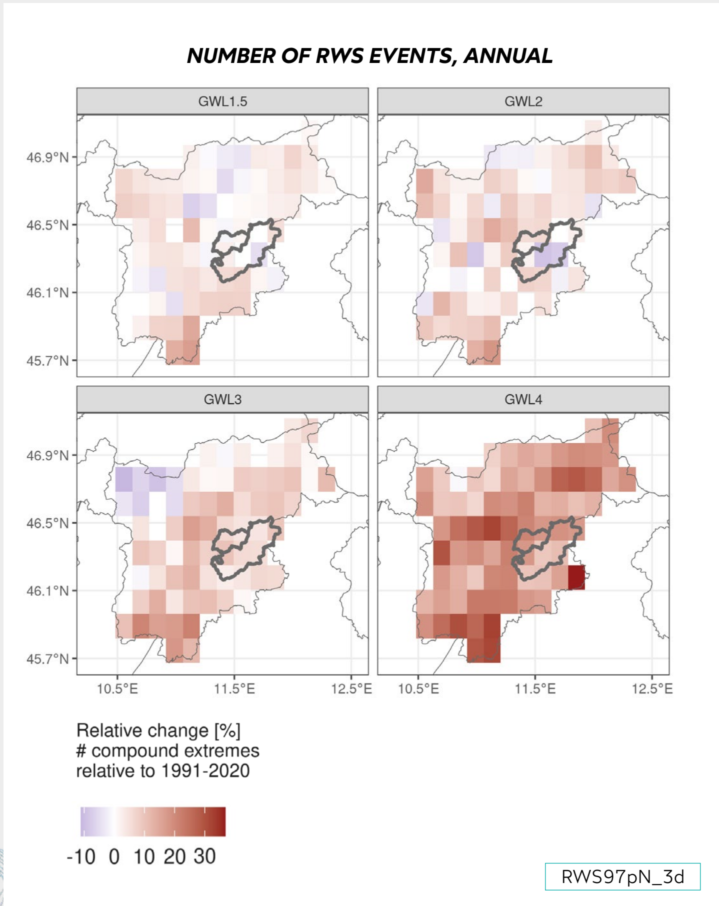
FIGURE 12: *Relative changes in annual maxima of precipitation (Rx1d) with respect to 1991–2020 under different Global Warming Levels (GWL). The values represent the median of bias-adjusted climate model simulations considered for the region.*



projected under GWL1.5 and GWL2 (***FIGURE 13***). For example, at the Cavalese station, the precipitation accumulated during the Vaia storm was 193.6 mm, which corresponds to a return period of 317 years in the current climate. However, with a global warming level of + 4 °C, the return period for this precipitation amount would drop to just 61 years.

On the contrary, based on the model ensemble of the original EURO-CORDEX simulations, no remarkable changes are projected for the intensity of wind speed extremes (WSx1d) in the future over the region. The same findings are also valid for the frequency of wind speed extremes (WS97pN_1d).

FIGURE 13: *Absolute changes in return periods associated with a Vaia-like precipitation event at station locations under different Global Warming Levels with respect to 1981–2020. Return periods are calculated based on the Regional Frequency Analysis applied to projected values of Rx3d.*



The projected changes of compound extremes of precipitation and wind are evaluated based on 3-day aggregated values of projected precipitation and daily maximum wind speed. The frequency of compound extremes of precipitation and wind (RWS97pN_3d) is projected to increase under all GWL scenarios, throughout the region, with a regional average between + 2.8 % (GWL1.5) and + 18.2 % (GWL4) events with respect to 1991–2020 (***FIGURE 14***).

The average magnitude of compound extremes of precipitation and wind (RWSx_3d) is also projected to increase under all GWLs, throughout the region (figure not shown). As also highlighted by the single variable analysis, the projected changes are mainly driven by the intensification of heavy precipitation, while wind extremes are not expected to significantly increase either in frequency or in intensity.

FIGURE 14: *Relative changes in the number of compound extreme precipitation and wind events (RWS97pN_3d) with respect to 1991–2020 under different Global Warming Levels (GWLs). The values represent the median of the original EURO-CORDEX simulations considered.*

METHODOLOGY

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 (number of days above/below threshold, extreme values) and trends 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.

REGIONAL FREQUENCY ANALYSIS (RFA) AND ESTIMATION OF RETURN PERIODS OF EXTREME EVENTS

The Regional Frequency Analysis (RFA) is employed for the assessment of the statistical distribution of extreme precipitation across Trentino – South Tyrol. RFA is a well-known scheme which is expected to reduce result uncertainty by using the data from multiple sites belonging to statistically homogeneous regions (Hosking and Wallis, 1993). The main homogeneous sub-regions for Trentino – South Tyrol are identified through a cluster analysis base on the *k-means* method on station features considering a set of indicators describing both precipitation regime and geographic characteristics. A Principal Component Analysis is applied prior to k-means to reduce the number of variables entering the clustering. The statistical homogeneity of the five identified sub-regions is finally assessed based on the L-moments (Hosking and Wallis, 2005).

The best fitting distribution of precipitation data for each identified sub-region is then selected from four tested distributions (Generalized Lognormal, GLO; Generalized Extreme Value, GEV; Generalized Normal, GNO; Pearson type III, PE3) by considering a goodness-of-fit metric based on the comparison of L-moments of fitted distributions and averaged sample L-moments within the sub-region. Fitted distributions are used to derive the return levels of daily precipitation associated to different return periods (RPs) and the RFA approach is applied to discuss RP estimates and variability of specific past events, such as 3-day precipitation intensity during the Vaia storm.

COMPOUND EXTREME EVENTS DETECTION AND ANALYSIS

A compound extreme event is identified when both precipitation and wind speed exceed the corresponding 97th percentile, as determined based on data over the baseline period (1991–2020). To investigate Vaia-like conditions, a compound extreme is identified when the 3-day precipitation exceeds the 97th percentile and daily wind speed maximum is above the threshold at least on one of the three days.

The compound extreme magnitude is computed at each location by multiplying the single variable standardized intensity (scaled using the mean and the standard deviation of the single variable over 1991–2020) and is set to 0 whenever either precipitation or wind speed does not exceed the corresponding 97th percentile. When using gridded datasets (CERRA reanalysis and climate models projections), the occurrence of compound extremes at local level is searched within a spatial buffer so that the concurrent exceedance can occur in the same cell or in its proximity.

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 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 periods, the 20-year GWL interval is extended over a 40-year period by adding 10 years before and after the 20-year interval. The changes are evaluated with respect to the 1981–2020 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.

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