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multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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2. ABSTRACT

Global warming is expected to lead to a significant increase of short and intense precipitation in the next future, with a specific impact on flood, flash floods and associated hydro-geomorphic processes (such as shallow landslides and debris flows). DV 2.4 reports on the work aimed to develop an integrated methodology to assess the impact of climatic variations and changes on the intense precipitation, and on the ensuing triggering of flood, flash floods and debris-flows over Italy, with a specific focus on ungauged, small-to-medium size basins. To meet this main objective, DV2.4 develops based on a number of scientific advances. The first advance is the advent of Convection-Permitting Models, which substantially improves the representation of precipitation at the sub-daily scales compared to the standard Regional Climate Models. However, due to the computational costs of these high-resolution simulations, often outputs for only short (typically ten years) time slices are available. These time series are too short to provide reliable statistics of extremes if analyzed using the traditional extreme value theory. This limitation can now be overcome by exploiting a second recent advance in the field of extreme value theory, the Metastatistical Extreme Value Distribution. A third scientific advance is represented by the current availability of weather generators which, when calibrated to describe specific climate windows, can suitably assist in the simulation of long time series of climatic (precipitation and temperature) forcing and in the ensuing flood response, thus helping to analyse changes in the flood response. Here, the novel statistical methods and the new generation of weather generators are further developed and exploited to quantify changes through the end of the current century in the frequency of i) extreme precipitation over whole Italy and ii) of flood/flash flood response and of debris-flow frequency for six selected key study areas (Proof of Concepts) where detailed process observations are available.

This Deliverable reports on four different contributions from RETURN – SPOKE WATER on this topic, as follows:

- Assessing and explaining future changes on sub-daily precipitation extremes using an ensemble of convection-permitting models, Univ of Padova;
- Evaluating sub-daily extreme precipitation from an ensemble of convection-permitting simulations: the role of topography. Univ. of Padova;
- Comparing extreme sub-daily rainfall projections from temperature-scaling and convection-permitting climate models across an Alpine gradient. Univ. of Padova;
- Projected amplification of rainfall extremes due to warming-induced reduction of snow fraction: an assessment based on convection-permitting simulations. Univ. of Padova.
- Non-stationary frequency analysis of extreme precipitation over Italy using projections from a Convection Permitting Model. Univ. of Florence.
- Assessment of convection-permitting sub-daily extreme precipitation simulations over Italy. Univ. of Florence.
- Flood frequency elasticity to extreme precipitation: a practical approach for Climate Change projection of flood probabilities. Politecnico di Torino

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4. Enhanced models of the flood response for small, ungauged basins, under climate change forcing

4.1 Assessing and explaining future changes on sub-daily precipitation extremes using an ensemble of convection-permitting models.

University of Padova

Anticipating and understanding the future evolution of intense precipitation events is crucial for improved risk management, especially in regions with mountainous terrain and urban areas vulnerable to natural disasters from extreme weather. Convection-permitting climate models (CPMs) operating at kilometer scales realistically depict convective precipitation mechanisms and complex terrain, enhancing the description of sub-daily extreme precipitation. However, their computational demands restrict simulations to short time periods (10-20 years), and limit the availability of ensemble members, hindering the evaluation of extreme event change and associated uncertainty.

This study employs an innovative non-asymptotic extreme value approach, proven effective in estimating rare return levels with reduced stochastic uncertainty even from short datasets, and which can help in providing insights on the changing processes. We apply the Simplified Metastatistical Extreme Value distribution (SMEV) to estimate the projected changes in future extreme sub-daily precipitation in a region characterized by complex terrain—specifically, the North Italy area encompassing both lowlands and the Italian Alps. Our analysis focuses on an ensemble of 9 CPMs from the CORDEX-FPS project, with a spatial resolution of 3 kilometers. We investigate three time periods: historical (1996-2005), near future (2041-2050), and far future (2090-2099) under the RCP8.5 emission scenario. We estimate return levels up to a 1% yearly exceedance probability (100-year return time) for precipitation durations from 1 to 24 hours. Their future change is evaluated at each grid point, conducting a permutation test to assess the statistical significance of the changes.

Results indicate a general increase in extreme precipitation across the domain and all durations, with spatial patterns of significant changes varying with durations, time period, and location. A pronounced increase occurs in some of the mountainous areas: at short durations in Eastern Alps, and across all durations in the northern Apennines. The western Alps and surroundings show moderate and not-significant change. Leveraging SMEV's ability to separate precipitation intensity distribution from event occurrence, we also examine the change in distribution parameters to interpret the shift in return levels in term of changes in thermodynamics (linked to temperature and water vapor content) and atmospheric dynamics controls. Interestingly, thermodynamics seems to be driving significant changes at short durations, while small-scale local dynamics contribute across all durations. Differences emerge between the Eastern Alps and Northern Apennines, with the latter showing a stronger intensification of intense versus moderate extreme events.

These findings provide valuable insights towards quantifying and understanding the future changes in precipitation extremes, benefiting stakeholders involved in risk management and design of adaptation measures

4.2 Evaluating sub-daily extreme precipitation from an ensemble of convection-permitting simulations: the role of topography.

University of Padova

Past studies have shown that in orographically complex terrain, observed extreme precipitation intensity are impacted by elevation in different ways at different durations. Convection-permitting climate models (CPMs) are receiving increasing attention thanks to the more realistic representation of extreme sub-daily precipitation compared to coarser climate models. Two almost still unexplored themes concern: i) CPMs ability to represent the observed relationship between precipitation and topography and ii) how the model ensemble uncertainty depends on elevation. To address these questions, we evaluate sub-daily extreme precipitation from an ensemble of eight CPM members (reanalysis-driven simulations) on topographically diverse terrains. We use observed data from rain gauges as benchmark. The analysis is conducted over the Eastern Italian Alps, where a strong relationship between precipitation sub-daily extremes and topography is observed (Dallan et al., 2023). We apply a non-asymptotic statistical approach (Simplified Metastatistical Extreme Value, SMEV) to estimate extreme precipitation return levels and assess their intra-model and inter-model uncertainties using a bootstrapped samples method. It is shown that the ensemble mean describe in a realistic way the precipitation extremes,with fractional standard errors of the mean-over-the-ensemble return levels ranging between 0,16 (24 hr duration, 2 yr return time) to 0,41 (1 hr duration, 100 yr return time). We found that, compared to rain gauges, CPMs systematically underestimate extreme return levels in lowlands, whereas overestimate them at higher altitudes. Nevertheless, the CPMs can capture the relationship between rain depth and elevation, particularly important for 1-3 hrs duration. While the intra-model uncertainty decreases systematically with elevation at all durations, a more complex behaviour is observed for both inter-model and total uncertainty. These findings help to characterize the impact of elevation on the ensemble of CPM simulations, which is particularly required for the applications of these simulations for adaptation to future flood risk

4.3 Comparing extreme sub-daily rainfall projections from temperature-scaling and convection-permitting climate models across an Alpine gradient.

University of Padova

Understanding projected changes in sub-daily extreme rainfall in mountainous basins can help increase our capability to adapt to and mitigate against flash floods and debris flows. Here we compare the changes in extreme rainfall projections from apparent Clausius-Clapeyron (CC) temperature scaling against those obtained from convection-permitting climate model simulations. Temperature and precipitation projections are obtained from an ensemble of convection-permitting climate models (CPM), which are suitable to the task given their ability to explicitly represent deep convection and to resolve the mountainous topography. The CPM data provided by the CORDEX-FPS Convection project at 1-hour temporal and remapped to 3 km spatial resolution, cover historical and far-future (2090-2099) time periods under the extreme climate change scenario (RCP8.5). Due to the computational demands however, CPM simulations are still too short (typically 10-20 years) for analyzing extremes using conventional methods. We use a non-asymptotic statistical approach (the Metastatistical Extreme Value, MEVD, Marani and Ignaccolo, 2015) for the analysis of extremes from short time periods, such as the ones of CPM simulations. We use hourly precipitation and temperature data from 174 stations in an orographically complex area in northeastern Italy as a benchmark.

Results from our analysis reveal that the apparent CC temperature scaling method demonstrates effective performance when applied to 1-hour extreme rainfall projections and for hoigh return periods. However, its accuracy descreases as the precipitation duration increases, highlighting potential limitations in accurately predicting changes in longer-duration extreme rainfall. Variations in performance are also noted when considering different return periods, as we find CPM changes depending on them, contradicting traditional CC-scaling.. Furthermore, we show that elevation is a key factor influencing temperature variations, with higher elevation locations experiencingmore pronounced temperature increases with respect to lowland areas. This affects more the results for 1 hr extreme rainfall projections, whereas it is less relevant for 24-h duration. These findings identifies some serious limitations of traditional CC scaling and emphasize the need for a nuanced understanding of the scaling method's applicability under various conditions.

4.4 Projected amplification of rainfall extremes due to warming-induced reduction of snow fraction: an assessment based on convection-permitting simulations.

University of Padova.

In mountainous regions, temperature determines the state of precipitation (liquid or solid) and in turn significantly affects runoff formation and flood generation. Projected temperature increase due to global warming may therefore affect the rainfall/precipitation ratio during heavy storms, hence intensifying the flood regime. This study aims to assess the projected variations in liquid/solid fraction of precipitation during heavy precipitation events in the upper Adige River, Italy (Eastern Italian Alps). The study utilizes simulations from an ensemble of convection-permitting climate models (CPM), which are suitable to the task given their ability to explicitly represent deep convection and to resolve the mountainous topography. The CPM data are delivered from the FPS-CORDEX project, available at 1-hour temporal and remapped to 3 km spatial resolution, and captures historical and far-future (2090-2099) time periods under the extreme climate change scenario (RCP8.5). Observational data from the densely instrumented river system are utilized for bias evaluation. Lastly, the Simplified Metastatistical Extreme Value (SMEV) approach, known for the reduced uncertainty compared to conventional approaches, is incorporated for frequency analysis. This method proves particularly useful for analyzing extremes from short time periods, such as those in CPM simulations. Eventually, the projected changes in sub-daily mean areal precipitation and mean areal liquid rainfall return levels are examined at various spatial scales based on the sub-basins total area. Our preliminary results underscore the significance of leveraging advanced statistical techniques and high-resolution climate models to address emerging challenges in hydrology and climate science. The climate-induced shifts in return period of liquid precipitation identified in this study are expected to have implications for both water resources management and adaptation measures.

4.5 Non-stationary frequency analysis of extreme precipitation over Italy using projections from a Convection Permitting Model.

University of Florence.

Climate change is changing the intensity and frequency of extreme precipitation. Understanding the impact of climate change on extreme precipitation quantiles is fundamental for managing flood risk and taking adaptation measures. Convection-Permitting Models (CPM), run at spatial resolutions for which deep convection is resolved (≤ 4 km), have been demonstrated to be more accurate than Regional Climate Models (RCM, ~10 km resolution) in describing the intensity of extremely short-duration events.

This study uses the projections of a CPM to evaluate quantiles of precipitation extremes at the national scale (Italy) with a high spatiotemporal resolution. Indeed, VHR-PRO_IT, a recent downscale product of the CMCC model at a convection-permitting scale of 2.2 km, with 1h temporal resolution, is used as a dataset. So far, this is the only CPM projection that covers the entire Italy in both emission scenarios (RCP 4.5 and RCP 8.5) and for a temporal coverage of 90 years (1981-2070).

A non-stationary implementation of the Simplified Metastatistical Extreme Value (SMEV) non-asymptotic approach is used to evaluate continuous changes in precipitation quantiles for different durations (1h, 3h, 6h, 12h and 24h) over the period 1981-2070 (1981-2005 historical + 2006-2070 emission scenarios). We adopt a two-parameter Weibull distribution to model the marginal distribution of the ordinary precipitation events. Three different models are compared: i) a stationary SMEV, with the two parameters constant over the entire time series; ii) a non-stationary model in which the higher-order parameter is kept constant; iii) a fully non-stationary model in which both parameters are allowed to change linearly in time.

The results show a clear geographical organization of the projected changes, with both increases and decreases in precipitation quantiles depending on the zone, the emission scenario, the precipitation duration and the return period of interest. The non-asymptotic approach allows us to discuss the results in terms of dynamic and thermodynamic drivers.

4.6 Assessment of convection-permitting sub-daily extreme precipitation simulations over Italy.

University of Florence.

Convection-permitting climate models have the potential to capture crucial processes in the climate system, presenting an opportunity to significantly enhance climate projections by providing more accurate representations of precipitation extremes. In this work, we conduct an evaluation of the accuracy of sub-daily precipitation extremes obtained from VHR-PRO_IT (Very High-Resolution PROjections for Italy, Raffa et al., 2023) over the Italian peninsula,. VHR-PRO_IT is generated through dynamic downscaling of the Italy 8km-CM climate projection at approximately 2.2 km resolution under the IPCC RCP4.5 and RCP8.5 scenarios, employing the Regional Climate Model COSMO-CLM.

Gauged locations are used to assess the accuracy of VHR-PRO_IT in reproducing observed extremes. More specifically, the observed dataset used as ground truth for the comparison is I2-RED (Improved Italian – Rainfall Extreme Dataset; Mazzoglio et al., 2020). For this work, 742 rain gauges covering the entire country with a minimum of 30 years of short-duration (1, 3, 6, 12, 24 h) annual maximum rainfall depths recorded from 1980 to 2022 are used. Conversely, the dataset derived from the VHR-PRO_IT climate projections includes annual maxima from a 30-year time series, connecting the historical period (1981-2005) with 5 years of the RCP8.5 scenario (2006-2010) of the CPM. Return levels are obtained for both dataset by means of a GEV distribution and inform the assessment of the CPM simulations.

Preliminary results outline the quality of the CPM simulations, especially at 24 hours duration, and show the impacts of return period, seasonality, elevation, latitude and proximity to the sea on the CPM model deviations. The results from this work are expected to have implications for both water resources management and adaptation measures.

4.7 Flood frequency elasticity to extreme precipitation: a practical approach for Climate Change projection of flood probabilities.

Politecnico di Torino

Flood risk management institutions and practitioners need reeliable and easy-to-use approaches that incorporate the changing climate conditions into flood predictions in ungauged basins. The traditional approach to regional flood frequency analysis enables the estimation of hydrological variables under stationary conditions. However, it is nowadays crucial to develop innovative techniques that consider the non-stationarity of climate variables. The present work aims at implementing an operative procedure to include the expected variation in precipitation extremes into regional analysis. We compare the Flood Frequency Curves (FFC) and the Intensity-Duration-Frequency (IDF) curves defining a relation between them through the elasticity, an indication of the sensitivity of floods to precipitation extremes. Under the assumption that this relation does not change in time, we obtain modified FFC according to the projections of an ensemble mean of 25 Cordex simulations of CMIP5. This methodology was applied to 227 catchments of the Po River basin in northern Italy. Elasticity values range between 0.5 and 2: the lowest values were found in Valle d'Aosta region, and the highest in the south-western part of Piemonte. Over the Po river basin, the percentage increase of the 100-year floods ranges between 15% and 40%. The most relevant increase of flood discharge is found in the area between Liguria and Emilia-Romagna in the southern part of the Po River basin, where the projected increase of precipitation extremes is the highest