Finanziato dall'Unione europea
NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate
Codice progetto MUR: **PE00000005** – **I33C22006910006**

Deliverable title: Hazard indicators under the impact of convective events at the Mediterranean scale

Deliverable ID: 8.4.4

Due date: 31 March 2026

Submission date: 30 March 2026

AUTHORS
Maria Vittoria Struglia (ENEA); Marta Antonelli (ENEA); Emanuela Pichelli (ENEA); Alessandro Anav (ENEA); Alessandro Dell'Aquila (ENEA); Sandro Calmanti (ENEA), Franco Catalano (ENEA), Giovanna Pisacane (ENEA); Gianmaria Sannino (ENEA); Marco Marani (UniPd); Marco Borga (UniPd); Piero Devò (UniPD); Chiara Cesali (FS Engineering); Vincenzo Rotella (FS Engineering); Cozzuto Giovanni (FS Engineering)

Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months) - Extension March 2026

Deliverable No.	DV8.4.4
Dissemination level*	CO
Work Package	WP4 - Towards a regional high-resolution convection-permitting climate model for weather scenario generation
Task	T8.4.4 - Reassessment of hazard indicators for future climate under the impact of convective events
Lead beneficiary	ENEA
Contributing beneficiary/ies	UNIPD, FS ENGINEERING

* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Lead contributor	Description
0.1	10.03.2026	Maria Vittoria Struglia, Marta Antonelli, Emanuela Pichelli (ENEA); Marco Marani, Marco Borga, Piero Devò (UNIPD); Chiara Cesali, Vincenzo Rotella, Giovanni Cozzuto (FS Engineering)	First draft
0.2	18.03.2026	Maria Vittoria Struglia, Marta Antonelli, Emanuela Pichelli, Alessandro Anav, Alessandro Dell'Aquila, Sandro Calmanti, Franco Catalano, Giovanna Pisacane, Gianmaria Sannino (ENEA); Marco Marani, Marco Borga (UNIPD); Chiara Cesali, Vincenzo Rotella, Giovanni Cozzuto (FS Engineering)	Critical review and proofreading
0.3	25.03.2026		Edits for approval
1.0	31.03.2026		Final version

Abstract

Based on the activities carried out in Task 8.4.4, this deliverable explains how extreme value statistics derived from CPM have been used to inform the design and implementation of risk-reduction strategies for critical infrastructure in future scenarios.

Specific studies were conducted in collaboration with FS ENGINEERING (GRUPPO FS), using a co-design approach to estimate the vulnerability and hazard level of their infrastructure assets to two major hazards: extreme precipitation events and heatwaves.

This report documents the methodology used to select relevant climate indicators, and the analysis performed on them to allow the selection of specific test sites.

Table of contents

Technical references 3

Document history..4

Abstract..6

Table of contents..7

List of Figures..7

List of Acronyms..8

Introduction..10

Description of climate scenario dataset..11

Codesign based methodology..13

Advancing climate change resilience for strategic infrastructures: extreme precipitation..14

Procedure for IDF curves update..14

The hydrological model..16

Results..19

Advancing climate change resilience for strategic infrastructures: heatwaves..23

Data and methods..23

Results..27

Conclusions..31

References..32

List of Figures

Figure 5.1: Scheme of co-design approach

Figure 6.1 Far-future vs historical percentage change of precipitation quantiles for the Esino basin: 1 hour duration at significant return periods.

Figure 6.2 Far-future vs historical percentage change of precipitation quantiles for the Esino basin: 12-hour duration at significant return periods.

Figure 6.3 Hydrological model of the Esino River Basin

Figure 6.4 Historical event for both calibration and validation of the hydrological model

Figure 6.5 The two-dimensional numerical model of the Esino River.

Figure 6.6 Water levels (from 2D numerical model and measured at the Camponocecchio stream gauge) during the flood event in 2013.

Figure 6.7 Peak flow discharges for different return periods (i.e. ARI 50 years and ARI 200 years) and both Camponocecchio and Moie locations

Figure 6.8 Flood areas around the selected bridge.

Figure 6.9 Freeboard computation at the selected bridge.

Figure 7.1: Climate model domain

Figure 7.2: Seasonal T2m climate projection for the three different scenarios

Figure 7.3 Summer Days Index computed on annual basis from the historical simulations over the 20 years reference period 1985-2004

Figure 7.4 Summer Days Index computed on annual basis for scenario simulations over the 20 years reference period: next future, mid future, far future.

Figure 7.5: 90th percentile of the maximum air temperature during different periods on the historical dataset: annual period (left panel) and the warm season (right panel)

Figure 7.6: Warm days above the 30°C threshold during different periods on the historical dataset: annual period (left panel) and the warm season (right panel)

Figure 7.7: Number of consecutive days above the 90th percentile of the maximum daily temperature

Figure 7.8: Climatic zonation of Italy for high temperature related indicators: proxy map of the high temperature (left panel); identified climatic zones (right panel)

Figure 7.9 Top panels - IDF curves for Pianura Padana: historical period (left panel); future projections (right panel). Bottom panels - IDF curves for Sicilia: historical period (left panel); future projections (right panel)

List of Acronyms

ARI: Average Recurrence Interval

CMIP6: Coupled Model Intercomparison Project – Phase 6

CN: Curve Number

CORDEX: COordinated Regional climate Downscaling EXperiment

CPM: Convection Permitting Model

D01: European domain of the climate model (15 km)

D02: West-Med and Italian domain of the climate model (5 km)

ECV: Essential Climate Variable

FPS: Flagship Pilot Studies

GHG: Green House Gas

HEC-HMS: Hydrologic Engineering Centre – Hydrologic Modeling System

ICTP: International center for Theoretical Physics

IDF: Intensity Duration Frequency

MEVD: Metastatistical Extreme Value Distribution

P: Precipitation

RCP: Representative Concentration Pathways

SCS: Soil Conservation Service

SSP: Shared Socioeconomic Pathways

T2m: Surface temperature (2 meters level)

WP4: Work Package 4

WRF: Weather & Research Forecasting Model

Introduction

The purpose of the activities carried out in this task was to provide support to FS ENGINEERING (GRUPPO FS) —the engineering company of the Italian railway network - in implementing risk reduction strategies against the hazardous occurrence of extreme events in a climate change scenario from a co-designed climate service perspective.

Users have indicated the technical need to assess the vulnerability of their infrastructure assets regarding the onset and persistence of weather and climate events above certain fixed thresholds dictated by the construction characteristics of certain devices (as in the case of heat waves) or for specific geographical areas potentially at risk (as in the case of flooding). This vulnerability assessment can inform the development of adaptation guidelines aimed at reducing climatic risks.

Reliable climate data are foundational to implement effective risk reduction strategies on critical infrastructures under future climate conditions. Traditional methods that rely exclusively on observational records or coarse-resolution climate model outputs have shown limited efficacy, as they either lack spatial detail or cannot reliably capture trends, changes in frequencies and durations as well as extremes relevant to long return periods.

For this type of application, data with a very high spatial resolution of a few kilometers is necessary, and Convection-permitting regional climate models are therefore essential. Throughout the project, spoke 8 aimed both to systematize the available data and deliver new, high-resolution regional climate projections. The aim was to expand the set of scenarios, as well as their spatial and temporal extent.

The activity was carried out in line with the spirit of the spoke itself, according to an approach already tested in the development of climate services. This interdisciplinary approach is based on continuous collaboration and discussion between the stakeholder (FS ENGINEERING, GRUPPO FS) and the spoke partners (ENEA and UNIPD). The aim is to first analyze needs and then resolve them using a co-design method.

Several innovations were introduced during this activity. Especially in the application of the newly produced high spatial resolution downscaling of CMIP6 climate projections, as well as the deployment of the Metastatistical Extreme Value (MEV) framework, a non-asymptotic approach to assess extremes when short time histories are available.

This report is organized as follows. First, the characteristics of the climate datasets used are briefly described, followed by the two distinct applications. The first application is aimed at studying the impacts of intense precipitation, while the second is aimed at studying the effects of abnormally hot and prolonged periods on stakeholder assets.

Description of climate scenario dataset

As explained in the introduction, Task 8.4.4 requires the extraction of climate information from datasets with a very high spatial resolution, based on models which are capable of explicitly resolving convective phenomena. On the other hand, to ensure statistical robustness of the results, it is advisable to use not a single realization of a model but a combination of several models/simulations, depending on the aspect that must be addressed. We briefly describe two different approaches.

- **Multi-model ensemble**. Each climate model provides only a partial representation of the Earth system that it aims to simulate. These limitations are linked to both the numerical characteristics of the models (the so-called dynamic core) and the parameterizations chosen for physical phenomena occurring at a smaller scale than that resolved by the model. Using different models under general conditions established in specific protocols that make them comparable, greatly expands the database on which we base the statistical analysis of the climate variables of interest, in the hope of approximating the behavior of the real system. Currently, the largest set of this kind has been produced in the CORDEX framework (FPS CONV CPM ensemble - Flagship Pilot Studies on Convection Permitting Models - Coppola et al., 2020; Ban et al., 2021, Pichelli et al., 2021) for present climate and under the RCP8.5 scenario. Future projections have been produced for two distinct time-slices, each one ten years long, at mid-century and at the end of the century. Relying on dataset produced within the FPS CONV CPM experiment, Fosser et al.,2024 provided new understanding of the changes in local precipitation extremes and related uncertainties over the greater Alpine region. Data from different models were conservatively remapped on a common regular grid and were made available through the RETURN Digital Ecosystem to overcome the limitation due to the relatively short time series, the Meta-statistical Extreme Value Distribution (MEVD, Marani and Ignaccolo (2016); Devò et al. (2025)) approach was used. This approach allows us to extract maximal information from short time series. The integration of MEVD inference with high-resolution CPM outputs allows us to obtain robust quantile estimates while maintaining the fine spatial structure of precipitation fields. Extreme precipitation change scenarios were produced using a 9-member ensemble, enabling a significant reduction in epistemological uncertainty. The RCP8.5 scenario was adopted following the European Commission Technical Guidelines for infrastructure climate proofing (European Commission, 2021).
- **Multi-scenario approach.** Although the scientific community regularly defines and updates different hypothesis for the combination of future Green-House Gases (GHGs) emissions with socio-economics possible evolutions (i.e. the SSPs scenarios), in line of principle we don't know which scenario or combination of scenarios will become real. Therefore, inevitably having to compromise due to the enormous computing and storage resources required, a possibility is to privilege the exploration of different scenarios and for long enough time intervals (several decades) with a single climate model. This approach allows to increase the statistics and evaluate, in a consistent and comparable way, the evolution under different scenarios. Within the fourth work package (WP4) of Spoke 8, we performed hindcast (i.e., ERA5-driven) and historical simulations (driven by the MPI-ESM1-2-HR model) to simulate the present (1980–2014) and future (2015–2100) climate under three different emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) with the WRF model at a resolution of 5 km and for the entire national territory. This configuration of the model has been proven to behave as a CP model, due to the use of a scale-aware parameterization for the description of convective phenomena.

Details of this dataset can be found in Struglia et al.,2025 and in the deliverables D8.4.1 and D.8.4.2 of the RETURN project.

These approaches have been followed for the intense precipitation and heatwave case studies described in this report, respectively.

Codesign based methodology

Climate models help us to understand present and future climate variability. They are also crucial to the development of climate services, which aim to help communities implement climate adaptation plans and undertake risk management.

The sequence of steps required to create a climate service is as follows:

- identification of the climate data of interest

- extraction of information from the data

- stakeholder engagement to define the best set of indicators and verify the results

- use of the information by the user

However, to obtain valuable results these steps require continuous interaction and feedback between climate scientists and users.

During the last year of the project, a series of bilateral meetings were therefore held, initially aimed at describing what data was available and what the users' needs were. Useful information was then identified and prepared based on user needs, applying, for example, thresholds linked to the technical characteristics of the assets under study or relying on the awareness of the vulnerability of the territory where these assets are located.

The information prepared in this way was shared with the users, who carried out independent assessments, which were then discussed again with climate scientists.

Through subsequent discussions and adjustments, the information was finalized in its final form, with a feedback process between developers and users.

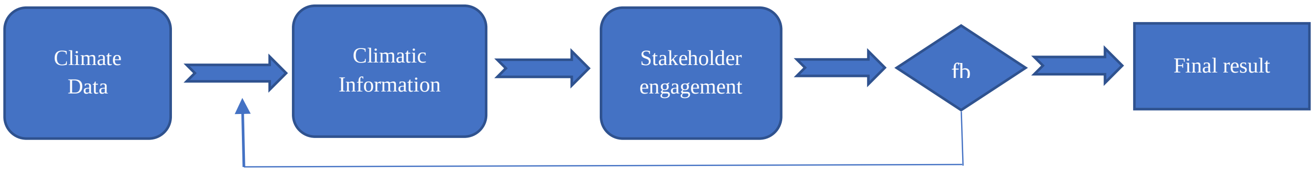


Figure 5.1 Scheme of co-design approach. 'fb' stands for specific feedback

Advancing climate change resilience for strategic infrastructures: extreme precipitation

Strategic infrastructure operators require robust estimates of how extreme precipitation will evolve under future climate conditions, emphasizing changes in intensity and frequency, especially for assets located in flood-prone areas. In this context, FS ENGINEERING (GRUPPO FS)— the engineering company of the Italian railway network—needs reliable estimates of future rainfall extremes to evaluate potential variations in peak river discharges and to plan adaptation measures aimed at reducing hydraulic risk along key railway corridors. Traditional approaches that rely exclusively on observational records or coarse-resolution climate model outputs have shown limited efficacy, as they either lack spatial detail or cannot reliably capture changes in extremes relevant to long return periods.

To address this need, we adopt a two-step framework. First, we use ground-based rainfall observations to construct Intensity–Duration–Frequency (IDF) curves, which represent the baseline statistical characterization of extreme precipitation in the present climate. Then, convection-permitting climate model (CPM) simulations (Ban et al.,2014) are employed to quantify projected climate-change-driven variations. Specifically, CPM simulations for historical and RCP8.5 future conditions are compared to derive spatially distributed percentage changes in rainfall quantiles. These change factors are then used to adjust the observationally derived IDF curves, yielding future IDF estimates that preserve observational reliability while incorporating physically consistent climate signals.

However, CPM datasets typically cover only about a decade, which is insufficient for stable estimation of rare-event quantiles. To overcome this limitation, we apply the Meta-statistical Extreme Value (MEV) framework (Marani & Ignaccolo, 2015, Devò et al.,2025), a non-asymptotic approach that leverages the full distribution of rainfall events to extract maximal information from short time series. The integration of MEV inference with high-resolution CPM outputs allows us to obtain robust quantile estimates while maintaining the fine spatial structure of precipitation fields.

The proposed methodology is deployed in the Esino river basin, within the Marche region, where a flood hazard assessment under projected climate change conditions is performed. The resulting Intensity-Duration-Frequency (IDF) curves are integrated by FS ENGINEERING (GRUPPO FS) into a calibrated hydrological model of the basin, to estimate the “future” flow hydrographs. Thus, these flow hydrographs are applied to a 2D numerical model aiming to simulate the flood propagation along the Esino river. The corresponding results show changes in the inundation areas as well as in water depth and flow velocity values which are critical factors for both the management of existing infrastructures and the design of new interventions or mitigation works to increase infrastructural resilience, along with climate risk analysis for future investments.

This study not only reveals methodological improvements in performing complex climate analysis but also narrows the gap between climate research and engineering design practice, known as the operational “last mile”, supporting climate-informed planning to increase resilience level of infrastructure systems.

Procedure for IDF curves update

For the study of the Esino basin, CPM grid cells were regionalized using a spatial clustering criterion based on the distance between centroids. The MEVD-S framework was applied to extract return-level estimates from each member of the CPM ensemble. The resulting CPM-derived quantiles were aggregated into a single representative field taking the median value between the CPM members at each grid cell.

The Percentage-change fields were then computed at each grid cell as:

$$\Delta_{\%}(d, RP) = \frac{h_{RCP8.5}(d, RP) - h_{historical}(d, RP)}{h_{historical}(d, RP)} \times 100$$

Where $h_{historical}$ and $h_{RCP8.5}$ are the return-level quantiles estimated from CPM outputs. These change factors were transferred to observation-based IDF curves:

$$h_{RCP8.5}(d, RP) = h_{obs}(d, RP) \times \left(1 + \frac{\Delta_{\%}(d, RP)}{100}\right)$$

This procedure preserves observational fidelity while incorporating physically-consistent climate signals from high-resolution CPM simulations.

The Percentage-change fields of extreme precipitation were calculated on a grid that covered the study area of the Esino basin. For each grid cell, changes were calculated for the selected durations and return periods by comparing future vs historical CPM-based quantiles. The median change between ensemble members was then applied to observation-based baseline IDF curves to obtain future scenario fields.

Figures 6.1 and 6.2 report examples of far-future percentage changes relative to the historical horizon, for different combinations of duration and return period.

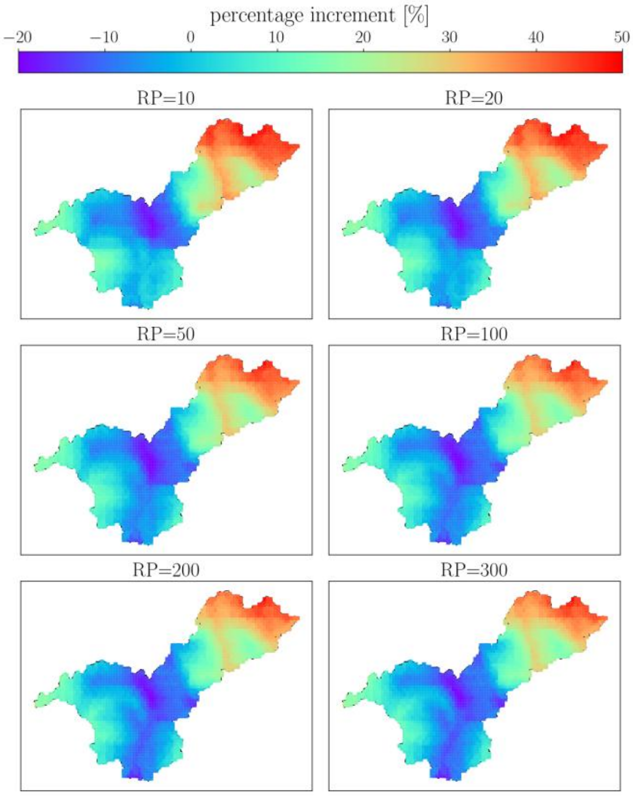


Figure 6.1 Far-future vs historical percentage change of precipitation quantiles for the Esino basin: 1 hour duration at significant return periods.

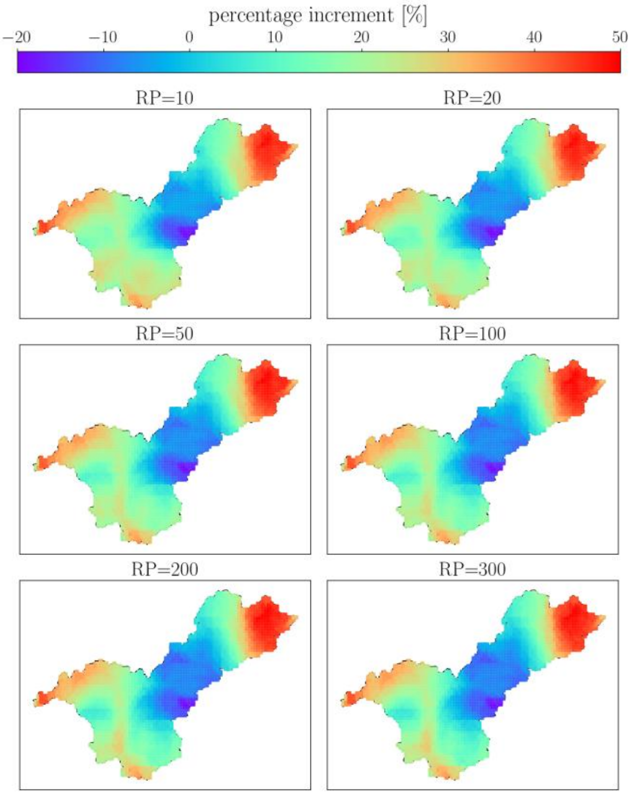


Figure 6.2 Far-future vs historical percentage change of precipitation quantiles for the Esino basin: 12-hour duration at significant return periods.

The hydrological model

A hydrological model of the Esino River Basin was implemented in the Hec HMS software (Feldman, 2000), based on the rainfall data previously collected and processed.

First of all, the basin's available data were collected including digital elevation models, land use maps and precipitation records to ensure accurate representation of the catchment area. Furthermore, the river network and sub-basins were delineated within the Hec HMS environment, defining reach lengths, slopes and connectivity between elements.
Secondly, the model has been configured to use the SCS method (Soil Conservation Service) for estimating rainfall runoff and infiltration, including the Chicago triangular hyetograph for rain intensity and peak timing, as well as the Curve Number (CN) method to simulate effective rainfall (i.e. direct runoff).

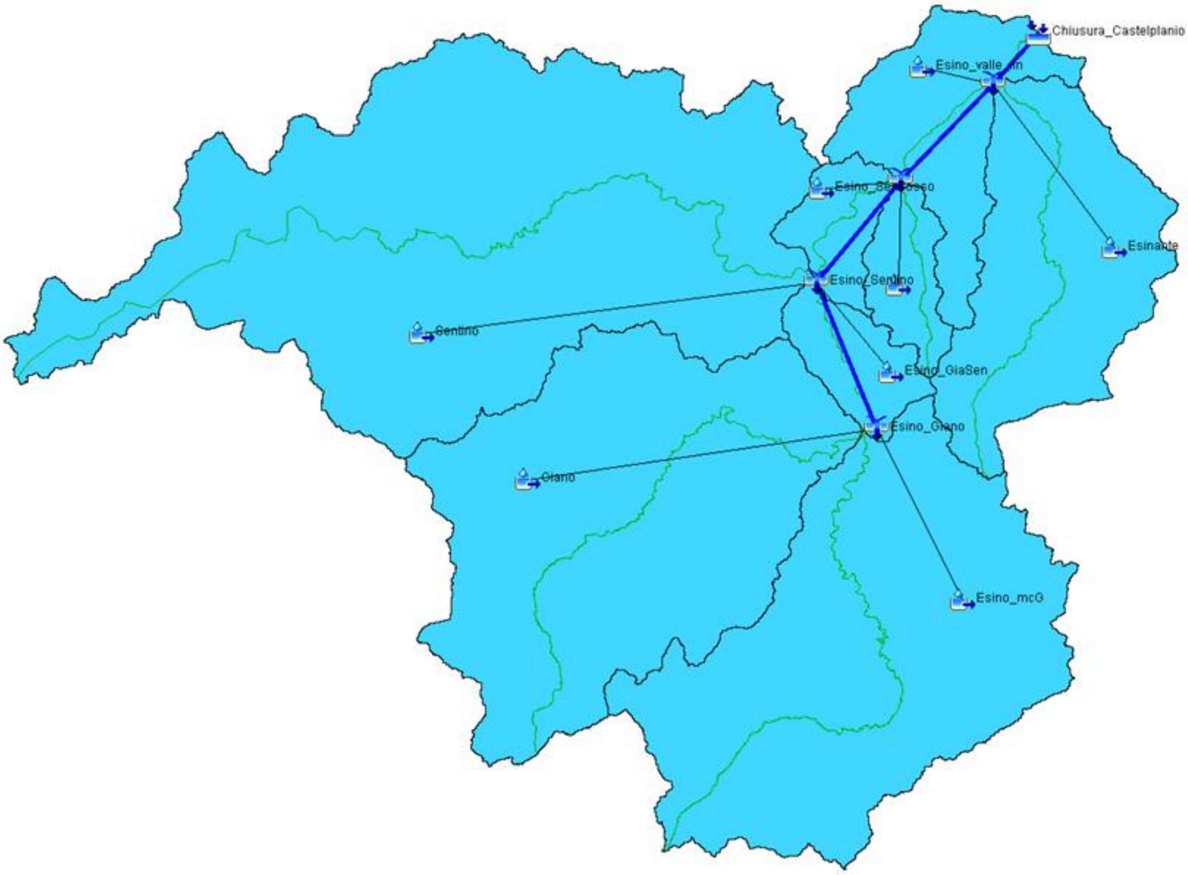


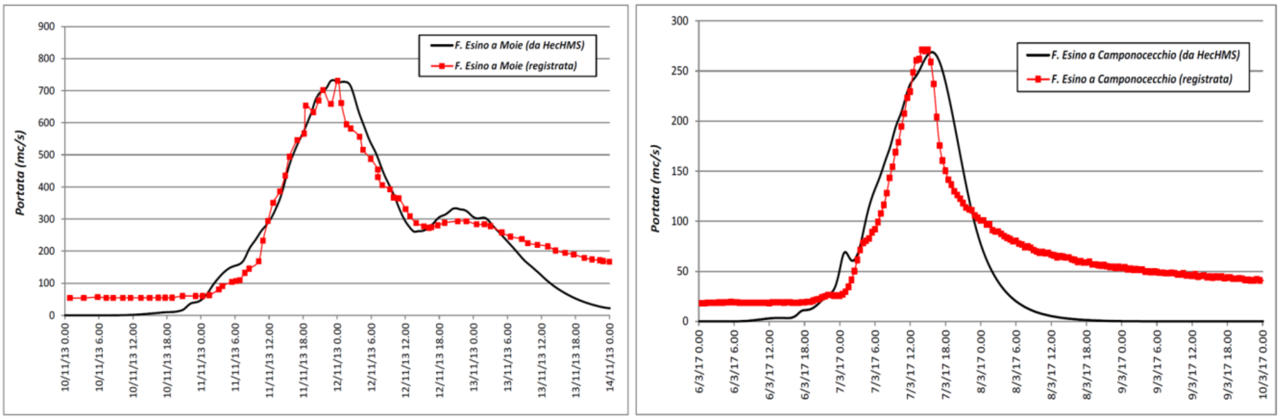
Figure 6.3 Hydrological model of the Esino River Basin

Calibration was performed using a thoroughly documented historical critical event (i.e., the event of November the 10th-13th, 2013), whilst the validation has been performed on another event (i.e., March the 6th-10th, 2017).

Two different stations have been used as control points and their measured flow hydrographs were considered:

- Camponocecchio stream gauge (located at the middle of the model) during the event on March the 6th-8th, 2017;
- Moie stream gauge (located at the end of the model) during the event on November the 10th-13th, 2013.

The following figure shows the good correspondence between the numerically computed and measured flow hydrographs.



(flood event in 2013) (flood event in 2017)

Figure 6.4 Historical event for both calibration and validation of the hydrological model

Thus, the computed Intensity-Duration-Frequency curves (IDF curves) for both current climate and future scenarios were used as input data of the hydrological model to simulate flow rates within the basin and to estimate the corresponding design flow hydrographs, to be applied to a numerical river hydraulic model.

Through the software *INFOWORKS ICM*, a two-dimensional numerical model of the Esino River under unsteady-state conditions was then developed to evaluate flood-prone areas and therefore support the computation of corresponding vulnerabilities and risks. Particularly, the 2D numerical domain covers the modelled stream, which is about 30 km long, and extends across an area of roughly 28 km^2.

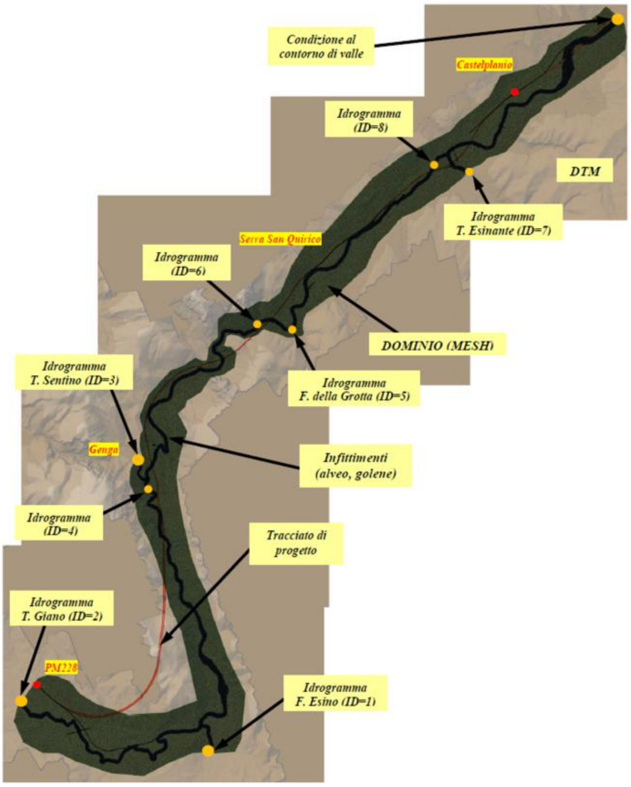


Figure 6.5 The two-dimensional numerical model of the Esino River.

As for the hydrological model, the hydraulic model was also calibrated in terms of roughness using the previously introduced documented historical critical event (i.e., the event of November the 10th-13th, 2013). The following figure shows the good correspondence between the numerically computed and measured water levels at Camponocecchio stream gauge.

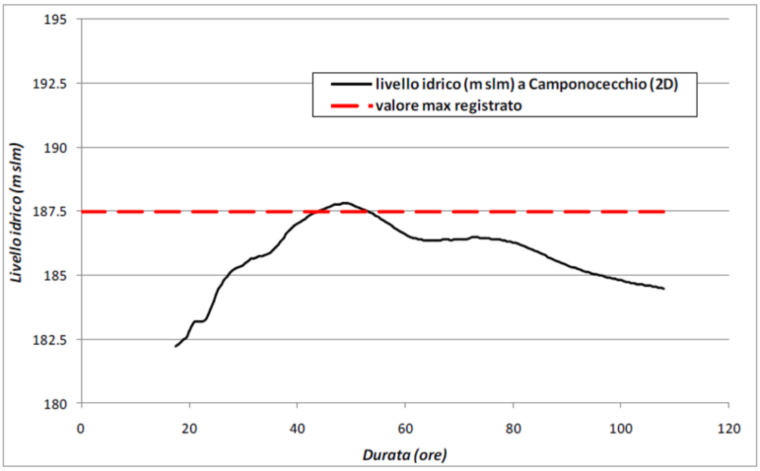


Figure 6.6 Water levels (from 2D numerical model and measured at the Camponocecchio stream gauge) during the flood event in 2013.

Finally, numerical simulations of the flood propagation along the Esino River were performed for the design ARI 200 year (Average Recurrence Interval), as well as for 50 years, for both the “current” and “future” climate scenarios.

Results

As shown from the previous hydrological analyses, the expected future increments in rainfall are +15,9% for Average Recurrence Interval of 50 years (ARI 50 years) and +17,2% for ARI 200 years.

The following figure shows the resulting flow hydrograph under the current and future scenarios.
It is worth observing that the above rainfall amounts induce an increase of approximately +24÷25% in peak flow discharges.

And specifically,

- the ARI 50 years peak flow discharge for future conditions is approximately equivalent to the ARI 200 years peak flow discharge for current climate conditions;
- the ARI 200 years peak flow discharge for future conditions is approximately equivalent to the ARI 500 years peak flow discharge for current climate conditions.

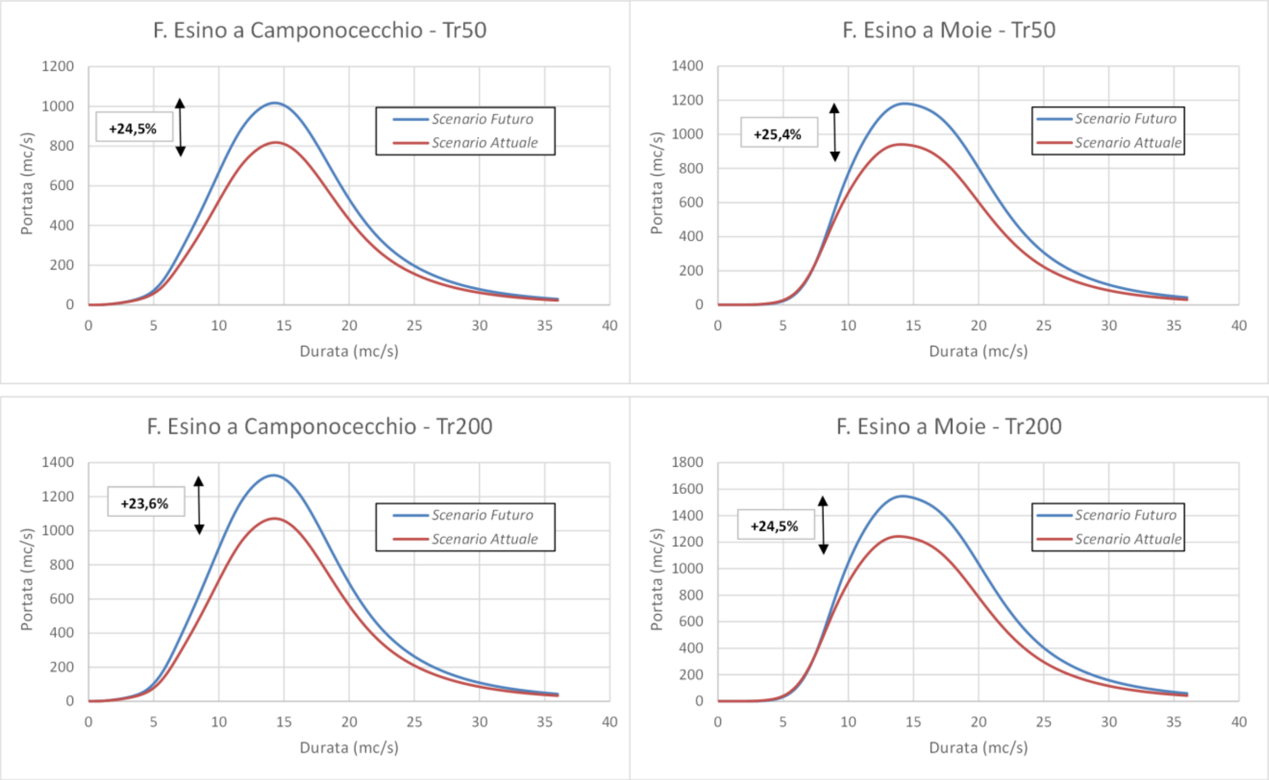


Figure 6.7 Peak flow discharges for different return periods (i.e. ARI 50 years and ARI 200 years) and both Camponocecchio and Moie locations

The results - in terms of flood areas and the corresponding water levels and flow velocities - of the numerical hydraulic model were used to analyze the vulnerabilities and risks along the existing railway and to support the design of the “new” railway.

For the sake of simplicity and example, the following figures show a “typical” analysis of an existing railway bridge, specifically located at the junction of the Sentino and Esino rivers.

Particularly, the freeboard (i.e. the minimum clearance between the bottom of the bridge structure and the high-water level design condition) under the ARI 200-years peak flow rate is reduced to zero for future scenario conditions.

Consequently, during the design phase of the new railway—currently under construction—the old bridge was decommissioned and replaced with a newly constructed viaduct.

This new river-crossing bridge has been properly dimensioned to meet the regulatory requirements established by Eurocodes and Italian structural and hydraulics rules, as under the future climate scenarios.

ARI 50 year (current scenario)

ARI 200 year (current scenario) ≡ ARI 50 year (future scenario)

ARI 500 year (current scenario) ≡ ARI 200 year (future scenario)

Photos of the existing railway bridge at the confluence between Sentino and Esino rivers

Figure 6.8 Flood areas around the selected bridge.

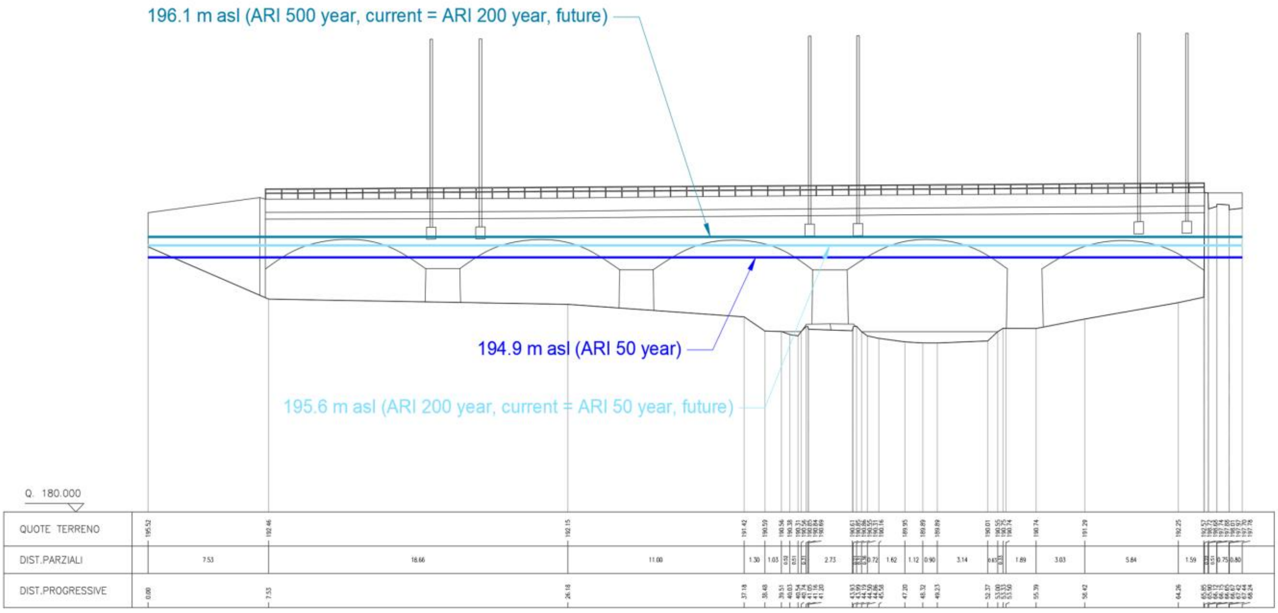


Figure 6.9 Freeboard computation at the selected bridge.

Advancing climate change resilience for strategic infrastructures: heatwaves

FS ENGINEERING (GRUPPO FS) —the engineering company of the Italian railway network – needs to estimate the hazard level as well as the vulnerability of infrastructural assets to the onset, the persistence and the frequency of events exceeding fixed high temperature thresholds. To address this need, a collaboration with ENEA – the National Agency for new technologies, Energy and Sustainable Economic Development – is established and a four-steps framework proposed.

First, based on the specific know-how on railways assets (FS ENGINEERING, GRUPPO FS) and climate modeling (ENEA), a selection of methods and indicators is performed to co-design and co-develop useful and usable climate information to feed effective services. To follow, high temperatures fixed thresholds are defined to maximize their representativeness to describe impacts on assets as well as statistical thresholds derived from the distribution of climate indicators itself (percentiles). Depending on these impacts-based indicators, a climate zoning of the territory that includes railways assets is computed: locations are aggregated by climate behavior; the maximum temperatures, heatwaves duration with different thresholds (fixed or statistics dependent), summer days indices, warm spell periods at different statistical thresholds are analyzed for the scope. Once the climate zones are defined, selected impact-based indicators are combined to compute statistical distribution per zone and therefore construct Intensity–Duration–Frequency (IDF) curves, in both the present and the future climate.

Innovation lies in the application of the newly produced high spatial resolution downscaling of CMIP6 climate projections (Struglia et al.,2025) and in deploying IDF curves to support a more efficient climate-informed management of the existent assets as well as to plan more resilient infrastructures in a climate change context.

Data and methods

For the current case study, we followed the multi-scenario approach already described in section 4. The results of downscaling CMIP6 global climate projections to local scales for the Mediterranean and Italian regions are used for the scope of this study. The chosen model is aiming to produce high-resolution climate information for the assessment of climate change signals, with a focus on temperature extreme events. Hindcast (i.e., ERA5-driven) and historical simulations (driven by the MPI-ESM1-2-HR model) were performed to simulate the present (1980–2014) and future (2015–2100) climate under three different emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5). The model configuration was chosen partly in accordance with the guidelines provided by the WRF modeling community for the coordinated runs in the context of the EURO-CORDEX CMIP6 protocol. A two-level nesting domain strategy has been carried out to downscale the coarse global CMIP6 data from a regional domain, covering the whole of Europe, to a fine spatial scale domain centered over Italy. Model domains used for the downscaling with the WRF regional model: European domain (D01 – 15 km), national domain (D02 – 5 km).

Figure 7.1 shows the model domain, for the current study we analyzed the results of the climate simulations, historical and projections, performed on the inner domain, i.e. the one at the highest resolution available at the time of the study (5km).

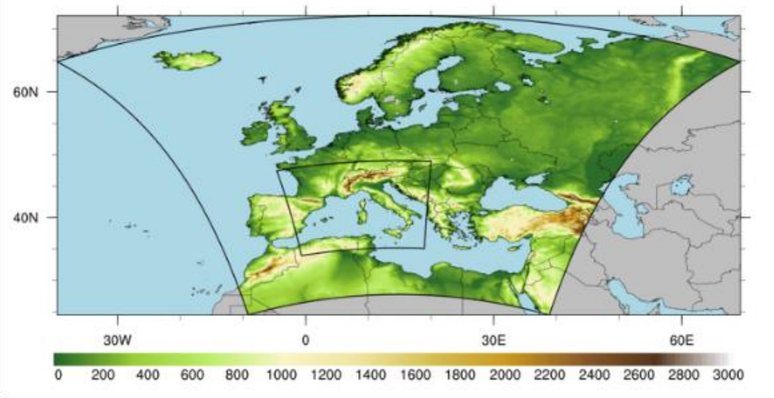


Figure 7.1 Climate model domain. D01 is the outer domain covering Europe and Mediterranean, D02 is the inner domain

The results of these climate projections were illustrated to the stakeholders, both during the regular Spoke meetings and during two different dedicated meetings. In the first one, the details of the simulations were explained and the results were shown, especially those that can be derived from a first analysis of the Essential Climate Variable (ECVs), especially surface air temperature (T2m) and total precipitation (P). As an example, Figure 7.2 shows the projections of T2m change at the end of the century: average difference between 2071-2100 and 1985-2014. Values at all grid points are significant at 10% level, assessed by Monte Carlo bootstrap procedure with 1000 repetitions.

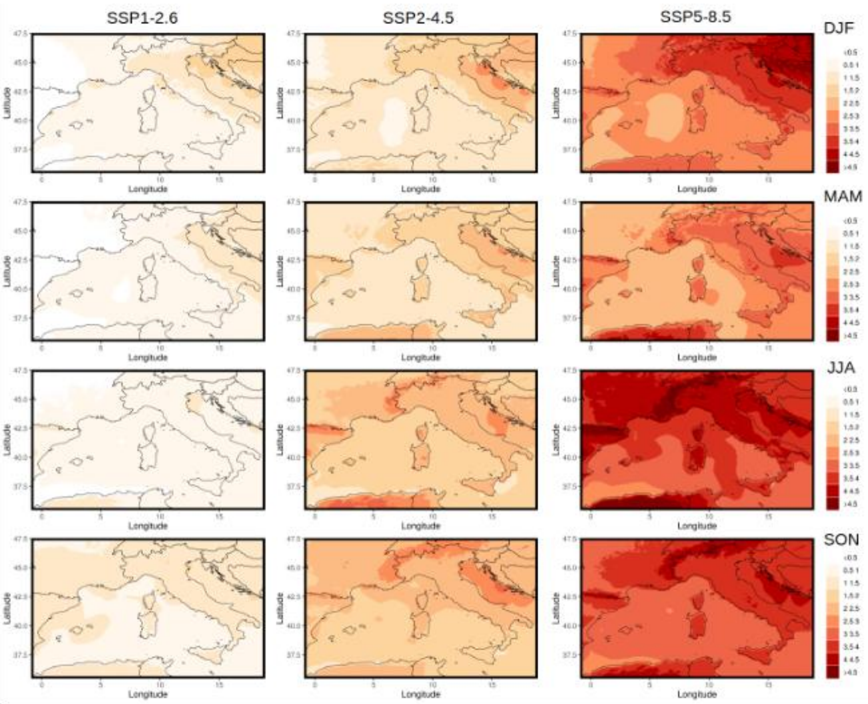


Figure 7.2 Seasonal T2m climate projection for the three different scenarios

Figure 7.2 clearly shows how average temperatures are set to rise in all scenarios, and even more so as the severity of the scenario increases. During this first meeting some users needed were first discussed and in particular their interest for the hazards related to extreme temperatures emerged.

Based on the findings of the initial discussions, ENEA calculated and proposed to stakeholders a series of standard temperature-related climate indicators based on climate data, in order to provide more accurate but also more concise quantitative information.

These indicators included calculating maximum temperatures for each season, calculating percentiles (75, 90, 95), calculating the Summer Day Index (i.e. the number of days above a given threshold, the standard one is 25°C) and the maximum number of consecutive Summer Days. In the second meeting these results were discussed and we agreed to recalculate certain indicators relating to heat waves (heat waves with various thresholds such as persistence, daily maximum, night-time minimum) based on the thresholds indicated by the user (30, 33, 35 degrees), on the basis of which the user then proceeded independently to calculate a microclimate zoning.

In particular, the Summer Day index was calculated both on an annual basis and over the warm season (extended to include June, July, August and September) for the user thresholds.

The 75th, 90th, 95th and 98th percentiles were also evaluated on both annual basis and warm seasons. The heatwave duration (at least 5 consecutive days over threshold) was evaluated with respect to the 75th percentile and for the fixed threshold of 35°C.

As an example of this extensive work done with the indicators, we show in figure 7.3 and 7.4 the Summer Days index evaluated for the historical period, and for different scenarios and time projections, respectively.

Figure 7.4 shows the SDI index computed for the most sustainable scenario (left column) SSP1-2.6 and for the most severe scenario (right column) SSP5-8.5. The SDI has been computed over 20-year periods, exploring three different time horizons: next future, mid-future and far future. The panels should be compared to figure 7.3 in order to appreciate the evolution with respect to current climate.

This intercomparison helps to understand in a glance what kind of changes may be expected depending on different scenarios and on temporal evolution.

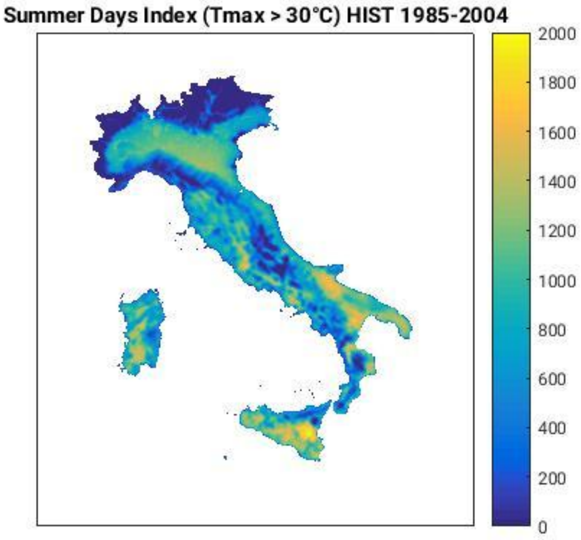


Figure 7.3 Summer Days Index computed on annual basis from the historical simulations over the 20 years reference period 1985-2004

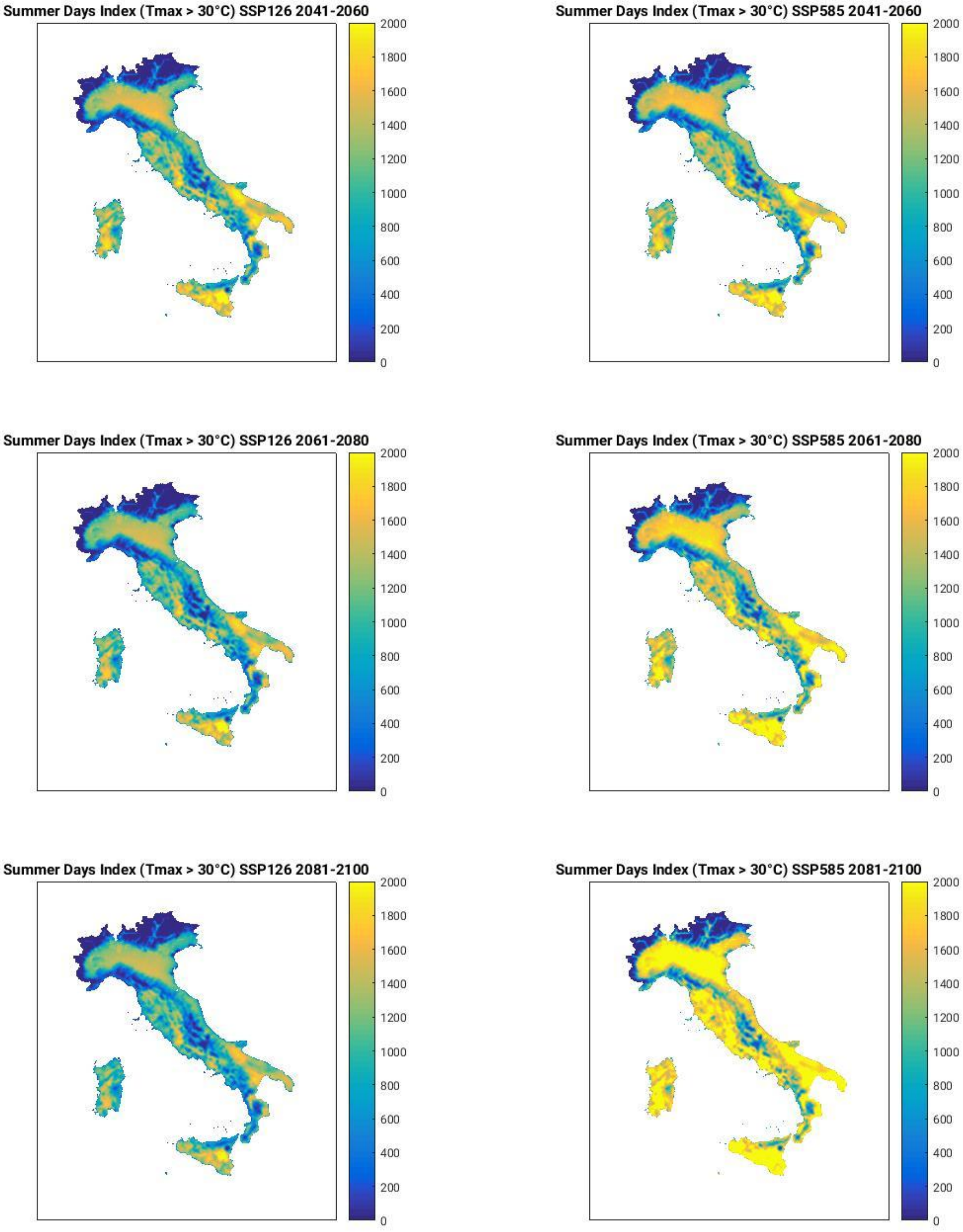


Figure 7.4 Summer Days Index computed on annual basis for scenario simulations over the 20 years reference period: next future, mid future, far future. The scale is the same as in fig 7.3

Results

The extensive analysis carried out on climate indicators had the scope to define impact-based indicators to describe the effects of high air temperatures occurrence on railways assets. Daily maximum air temperatures on both annual and warm season (June, July, August and September) basis were analyzed: different percentiles were computed, and the 90th percentile of the daily maximum temperature has been selected to be significant. Warm days were computed as well for different statistical and fixed thresholds, both on a yearly basis and for the warm season: the 30°C threshold is selected for the scope. Duration-based indicators are treated as a second order factor for describing main impacts on railways. For this preliminary analysis, the historical climate simulation was used.

Figures 7.3 and 7.4 show the spatial distribution over the national territory of the 90th percentile and of the frequency of warm days occurrence over 30°C, respectively. The left and right panel shows the yearly and warm seasons indicators, respectively. As expected, the restriction to the warm season mostly affects the percentile computation, whereas the fixed threshold computation is much less affected.

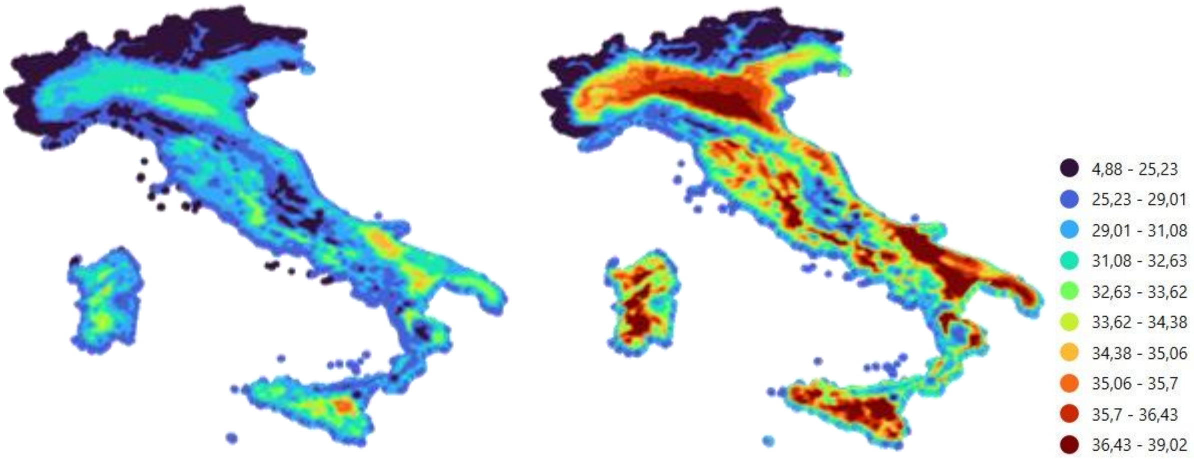


Figure 7.5 90th percentile of the maximum air temperature during different periods on the historical dataset: annual period (left panel) and the warm season (right panel)

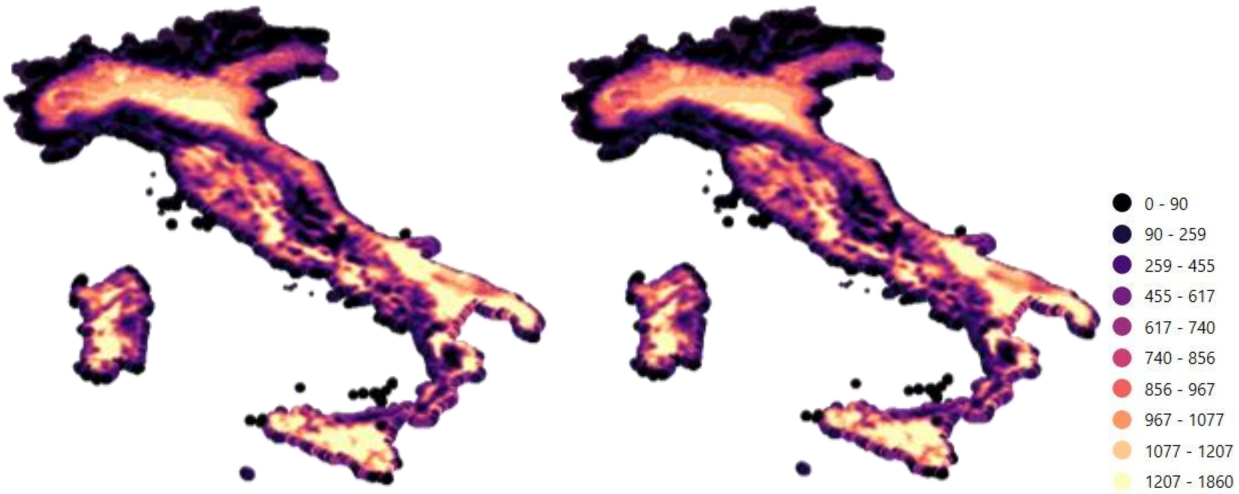


Figure 7.6 Warm days above the 30°C threshold during different periods on the historical dataset: annual period (left panel) and the warm season (right panel)

The small differences among the left and right panel of fig 7.4, detectable in the Po Valley and in zones of Southern Italy, show that the 30°C threshold has been occasionally hit and surpassed also in periods other than the months chosen to define the warm season (JJAS). As duration-based indicator, the number of consecutive days above the 90th percentile of the maximum daily temperature was chosen (Figure 7.5). Combining the information from figure 7.3 and 7.5 we can observe, as an example, that in the hottest spots of southern Italy it is possible, even in present climate conditions, to surpass periods two weeks long above 35°C. Even more prolonged periods can be found in the Po valley, although the 90th threshold is slightly lower (32.5 °C) than in Southern regions.

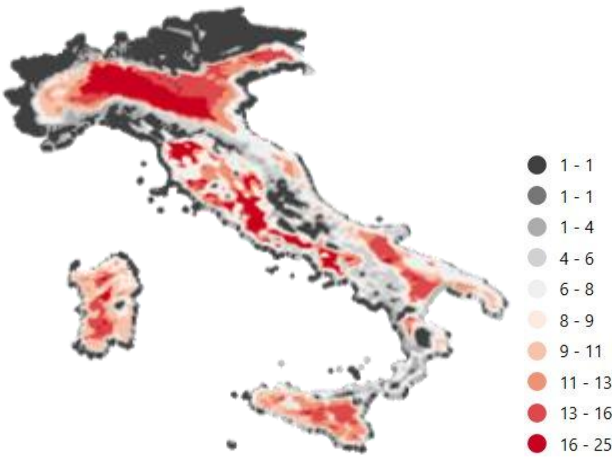


Figure 7.7 Number of consecutive days above the 90th percentile of the maximum daily temperature

A climatic zonation (Figure 7.6) is performed to define clusters with homogeneous temperature-related response. The 90th percentile of the maximum daily temperature on the annual basis is processed and scaled within a 0-1 range. Same procedure is performed on the warm days above 30°C on the annual basis indicator. To follow, these two maps are combined to deploy a proxy mapping of the high temperature impacts on railways. This latter is used as baseline to draw high temperature clusters: 23 climatic zones are identified. Two different zones are chosen as proof-of-concept areas and specific site IDF curves are computed for them. They have been indicated with a cross on the right panel of Figure 7.6

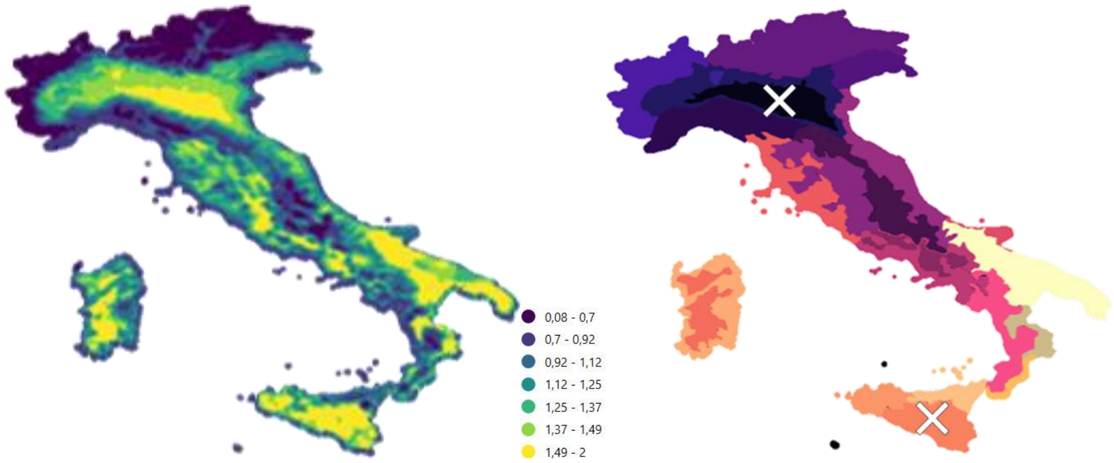


Figure 7.8 Climatic zonation of Italy for high temperature related indicators: proxy map of the high temperature (left panel); identified climatic zones (right panel)

Once the climatic zones are defined and the locations identified**,** intensity – frequency – duration (IDF) curves are computed for each location (climatic zones in Po Valley and Sicily, respectively). Extreme events selection is performed on both historical dataset (i.e. 1980-2014) and future projections dataset (i.e. 2015-2100 for SSP5-8.5 scenario which is the most severe): annual maxima analysis is computed on time histories and Gumbel statistical model is applied to assess probability levels and return periods (2, 3, 4, 5, 7, 10, 25, 50 years). Relevant results include the rise in temperature intensity of extreme events as well as the frequency at both the selected locations. The IDF curves have been computed for the apparent temperature, which consider the combined effect of temperature and humidity. This choice was made to better assess the effects of the heatwave on exposed individuals and not just on machinery.

The IDF functions are shown in figure 7.7. Coherently with the results of the climate projections, the intensity of the events increases for all the considered return periods with the worsening of the scenario represented. Reaching the critical threshold of 30 degrees is already a likely option in the current climate, especially in southern Italy, but the intensity of the most extreme events could worsen by +3 degrees even in the least pessimistic scenario, reaching +5 degrees in the most severe scenario.

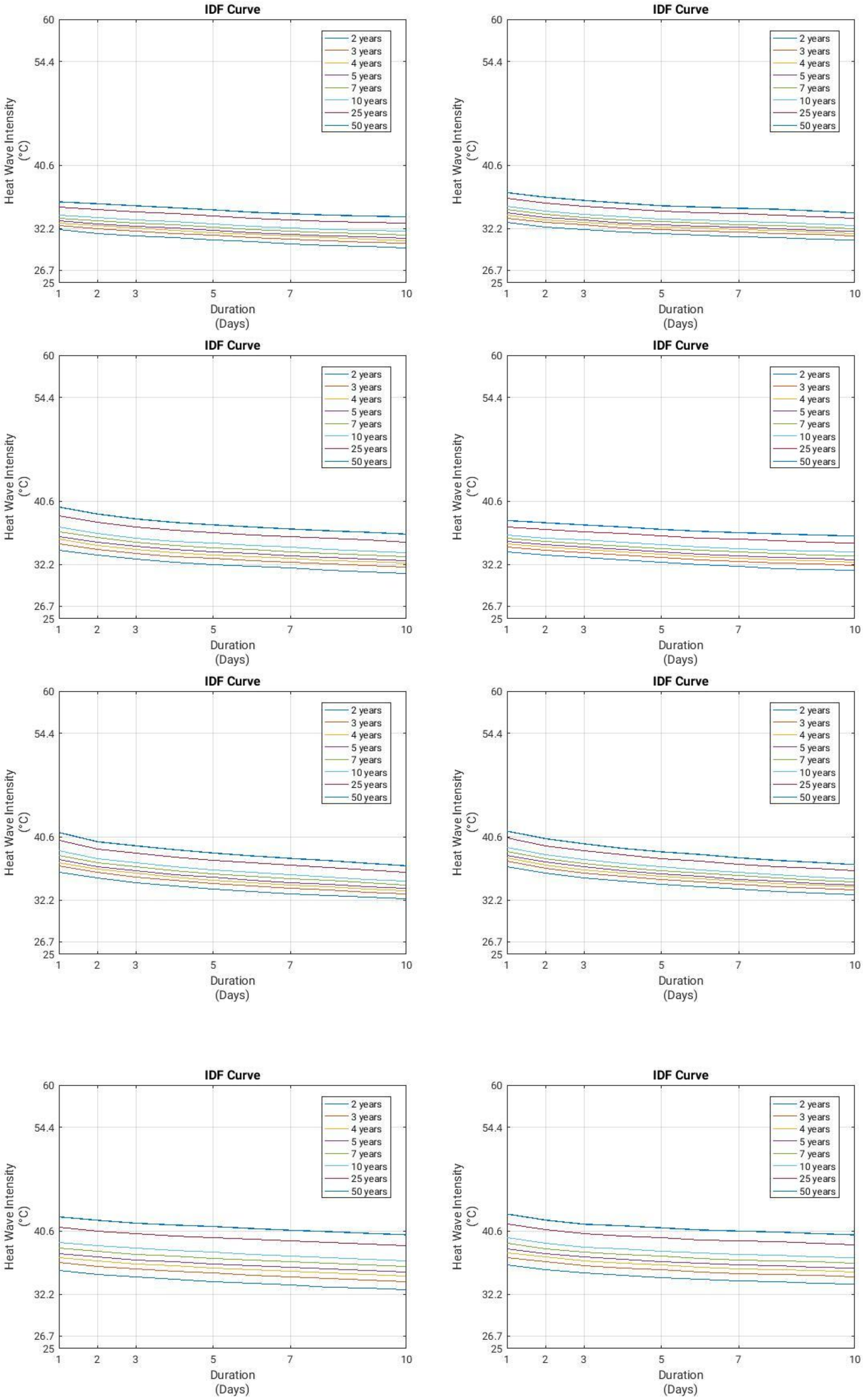


Figure 7.9 Left column: IDF curves for the selected point in Pianura Padana. Right column IDF curves for the selected point in Sicily. Rows: Different scenarios. From top to bottom: historical period, SSP126, SSP245, SSP585.

Conclusions

The focus and scope of the task was to support FS ENGINEERING (GRUPPO FS) to implement risk reduction strategies linked to the occurrence of extreme events in a changing climate.

Hazards linked to both high temperatures events and flooding events have been analyzed for specific locations and conditions suggested by the user, in a co-designed Climate Service perspective.

The scope was fully met during the last year of project, proving that the proposed approach and methodology helped to bridge the gap from climate data to climate information, with a potential positive impact on design and management strategies of the railway group.

As a result of the activity, FS Engineering gained robust information that helped to make informed decisions during the design phase of the new railway in the Esino river basin.

On the other hand, FS Engineering has been also enabled to define a nation-wide, up-to-date map of heat waves indicator, gaining insights in the heat-stress related risks under current and future scenarios. This knowledge is essential to plan countermeasures aimed to limit possible malfunctions in railway network equipment as well as to take care of heath stress for both travelling staff and users.

Although specific results of the activity have been tailored on the basis of user needs, the transferability to other stakeholders and/or to the evaluation of the impact of other kinds of hazards is ensured by the general methodology adopted.

References

Ban, N., J. Schmidli, and C. Schär (2014), Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations, J. Geophys. Res. Atmos., 119, 7889–7907, oi:10.1002/2014JD021478

Ban, N., Caillaud, C., Coppola, E., Pichelli, E., Sobolowski, S., Adinolfi, M., Ahrens, B., Alias, A., Anders, I., Bastin, S., Belušić, D., Berthou, S., Brisson, E., Cardoso, R.M., Chan, S.C., Christensen, O.B., Fernández, J., Fita, L., Frisius, T., Gašparac, G., Giorgi, F., Goergen, K., Haugen, J. E., Hodnebrog, Ø., Kartsios, S., Katragkou, E., Kendon, E.J., Keuler, K., Lavin-Gullon, A., Lenderink, G., Leutwyler, D., Lorenz, T., Maraun, D., Mercogliano, P., Milovac, J., Panitz, H.-J., Raffa, M., Reca Remedio, A., Schär, C., Soares, P. M. M., Srnec, L., Steensen, B. M., Stocchi, P., Tolle, M.H., Truhetz, H., Vergara-Temprado, J., de Vries, M.H., Warrach-Sagi, K., Wulfmeyer, V. and Zander, M.J.: The first multi-model ensemble of regional climate simulations at kilometer-scale resolution, part I: evaluation of precipitation. Clim Dyn 57, 275–302, doi:10.1007/s00382-021-05708-w, 2021.

European Commission,2021 - Commission Notice — Technical guidance on the climate proofing of infrastructure in the period 2021-2027 (OJ C, C/373, 16.09.2021, CELEX: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03))

Coppola, E., Sobolowski, S., Pichelli, E., Raffaele, F., Ahrens, B., Anders, I., Ban, N., Bastin, S., Belda, M., Belusic, D., Caldas-Alvarez, A., Cardoso, R. M. , Davolio, S. , Dobler, A. , Fernandez, J. , Fita, L. , Fumiere, Q. , Giorgi, F. , Goergen, K., Güttler, I. , Halenka, T. , Heinzeller, D. , Hodnebrog, Ø. , Jacob, D. , Kartsios, S. , Katragkou, E. , Kendon, E. , Khodayar, S., Kunstmann, H., Knist, S. , Lavín-Gullón, A., Lind, P., Lorenz, T. , Maraun, D., Marelle, L., van Meijgaard, E. , Milovac, J. , Myhre, G. , Panitz, H.-J., Piazza, M. , Raffa, M. , Raub, T. , Rockel, B., Schär, C., Sieck, K., Soares, P. M. M., Somot, S. Srnec, L. , Stocchi, P. , Tölle, M. H. , Truhetz, H. , Vautard, R., de Vries, H., and Warrach-Sagi, K. : A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. Clim Dyn 55, 3–34 doi:10.1007/s00382-018-4521-8, 2020

Devò, P., Caruso, M. F., Borga, M., & Marani, M. (2025). Estimates of rare rainfall extremes in ungauged areas. Geophysical Research Letters, 52, e2024GL113576. doi: 10.1029/2024GL113576

Feldman, A.D. (2000) Hydrologic Modeling System HEC-HMS: Technical Reference Manual. US Army Corps of Engineers, Hydrologic Engineering Center.

Fosser, G., Gaetani, M., Kendon, E.J. et al. Convection-permitting climate models offer more certain extreme rainfall projections. Npj Clim Atmos Sci 7, 51, doi:10.1038/s41612-024-00600-w, 2024.

Marani, M., & Ignaccolo, M. (2015). A metastatistical approach to rainfall extremes. Advances in Water Resources, 79, 121–126. doi: 10.1016/j.advwatres.2015.03.001

Pichelli, E., Coppola, E., Sobolowski, S. et al. The first multi-model ensemble of regional climate simulations at kilometer-scale resolution part 2: historical and future simulations of precipitation. Clim Dyn 56, 3581–3602, doi:10.1007/s00382-021-05657-4, 2021.

Struglia, M. V., Anav, A., Antonelli, M., Calmanti, S., Catalano, F., Dell'Aquila, A., Pichelli, E., and Pisacane, G.: Impact of spatial resolution on multi-scenario WRF-ARW simulations driven by the CMIP6 MPI-ESM1-2-

HR global model: a focus on precipitation distribution over Italy, Geosci. Model Dev., 18, 6095–6116, https://doi.org/10.5194/gmd-18-6095-2025, 2025.