multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

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Abstract

Based on the activities carried out in Task 8.4.3, this deliverable presents a proof of concept for the use of convection permitting models for assessing future extreme precipitation over Italy in the presence of climate change.

Simulations have been performed in the framework of a follow-up activity, assigned through a follow up call, by the Abdus Salam International Centre for Theoretical Physics (ICTP) Trieste.

This report documents the methodology used and statistics of the generated data, that will be shortly made available in a public repository.

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Introduction

One of the most destabilizing types of extreme events typical of mid-latitudes is **convective extreme precipitation**, which can manifest itself differently depending on the region. These events are defined through statistical metrics and are inherently region-dependent, as the same amount of precipitation may trigger floods and landslides in one area but not in another. This variability is largely due to the critical role played by local-scale interactions and feedback mechanisms, which also influence the spatial and temporal extent of such events.

Modeling extreme convective rainfall presents several challenges for climatologists. Perhaps the most significant is the mismatch between the small spatial scales at which convective processes occur and the much larger scales that can be resolved by conventional climate models. To address this issue, parameterization schemes are typically employed to represent the effects of convection at coarser scales. However, these schemes constitute one of the primary sources of uncertainty in climate simulations.

To overcome this limitation, it is necessary to achieve kilometer-scale resolution in order to explicitly represent the processes and interactions that are essential for realistic local climate modeling. By directly resolving convective processes—without relying on parameterization—high-resolution models can significantly reduce uncertainties associated with convective schemes in climate projections.

Moreover, increasing spatial resolution enables deeper investigation into the physical processes governing convection and its interaction with the atmosphere. This, in turn, can improve our understanding of the physics and thermodynamics of the climate system at small spatial scales and short temporal intervals.

In recent years, several coordinated international efforts have emerged to investigate convective precipitation events and their projected changes using ensembles of regional climate models capable of explicitly resolving convection. One such initiative is the **CORDEX-FPS Convection project**, which was established to provide a multi-model assessment of the capabilities of convection-permitting models (CPMs), deliver a robust and consistent evaluation of the impacts of climate change on convective events at local and regional scales, and explore new mechanisms and processes characteristic of these scales (Coppola et al., 2021; Ban et al., 2021, Pichelli et al., 2021).

Evidence to date indicates that, compared to traditional regional climate models (RCMs), CPMs substantially reduce model uncertainty across most statistical metrics. This improvement is likely due to the more realistic representation of local-scale dynamics in CPMs, which also facilitates a clearer emergence of the climate change signal (Fosser et al., 2024).

Results obtained so far are encouraging. For example, CPMs have improved the representation of spatial precipitation patterns and variability at daily and hourly timescales, as well as the frequency and intensity of precipitation events (Ban et al., 2014, 2021; Chan et al., 2020). They have also enhanced the simulation of the summer diurnal cycle of precipitation in terms of both timing and intensity at sub-daily scales, and improved the representation of extreme events (Kendon et al., 2012; Berthou et al., 2018; Ban et al., 2014; Prein et al., 2013a; Fosser et al., 2015; Fosser et al., 2017; Fosser et al., 2020). Additionally, these models have revealed different patterns of local climate change, although their robustness is still under investigation (Pichelli et al., 2021).

Through the application of tracking algorithms to ensembles of convection-permitting models, it has become possible to study the evolution of convective systems with varying precipitation characteristics (Muller et al., 2022) — something that was not feasible with either RCMs or global climate models (GCMs), due to their reliance on convective parameterization.

Beyond improvements in representing precipitation across spatial and temporal scales, CPMs have also demonstrated added value in simulating temperature compared to RCMs. Notably, differences have been identified in the intensity of simulated heatwaves, with CPMs generally producing hotter and drier conditions than their RCM counterparts (Sangelantoni et al., 2022).

Concept and Methodology

By aligning with these international directions, the present task of RETURN provides high-resolution, convection-permitting simulations with both fine spatial and temporal detail. These simulations cover multiple global warming scenarios and use a domain designed to encompass the entire Italian territory, including islands.

Dynamical downscaling is employed, starting from boundary conditions derived from a low-resolution global model, through multiple nesting using an intermediate-resolution regional model (approximately 12 km), similar to those used in the Euro-CORDEX framework.

A control simulation has been conducted using a convection-permitting model with a resolution of approximately 3 km, with a minimum duration of 10 years, directly nested within ERA5 reanalysis data. This simulation allowed validation of daily and hourly climatology for key variables relevant to hydrological and hydraulic modeling—such as temperature, precipitation, solar radiation, and surface mass and energy fluxes—as well as for the study of phenomena such as windstorms and associated precipitation events.

The final scenario simulation has been derived by using three time slices. The boundary conditions for the convection-permitting model have been provided by a regional climate model simulation at 12 km resolution, itself nested within a global climate model under one of the CMIP6 SSP scenarios.

The three time slices include:

- one 20-year period within 1990–2014, and
- two 10-year periods corresponding to different **global warming levels (GWLs)**.

The simulations covers a domain that includes the one previously used in the CORDEX-FPS Convection project, ensuring the possibility of estimating inter-model uncertainty.

The simulations carried here enable the extension of high-resolution climate simulations to the entire country of Italy, including islands, which until now have only been partially covered by previous initiatives such as CORDEX-FPS Convection. In addition, we provide a reference database for the Italian scientific community, supporting a wide range of research activities—from small-scale climate physics to impact assessment studies.

By extending the analysis of the effects of climate change on extreme precipitation to both daily and hourly timescales across the entire Italy, it is possible to estimate the response of river discharge in large, medium, and small basins. This also allows for the assessment of flood probabilities in both urban and non-urban areas, particularly in regions most affected by increases in peak discharge.

By employing algorithms capable of tracking the evolution of convective systems, we facilitate detailed investigations into the dynamical and thermodynamical evolution of such systems. This includes, for example, analyzing changes in the size and volume of convective storms, their propagation speed, the type of hydrometeors produced at the peak of precipitation events, and how these characteristics may be influenced by global warming.

The adoption of the **global warming level (GWL)** framework makes the simulations largely independent of scenario uncertainty. Since the effects of global warming are approximately linear for most dynamical and thermodynamical variables of the climate system, the regional response to emission scenarios can be decomposed into two nearly independent components:

1. the transient global response to emission scenarios, and
2. the regional response associated with a given GWL, which can be interpreted as *regional climate sensitivity*.

However, it is important to note that for certain variables—such as glacier and ice sheet volumes and sea-level rise—the response depends on the timing at which a given GWL is reached, due to the inherent inertia of these systems.

This approach provides more precise information on how the climate is expected to evolve under warming levels consistent with the goals of the Paris Agreement (i.e., stabilization at 1.5°C or well below 2°C). As such, it is particularly valuable for informing the development of effective mitigation and adaptation strategies (IPCC Chapter 11 CCB 11.1; Seneviratne et al. 2021).

Simulation model and domain

The H-ResIT project will employ the **RegCM5 model** (Giorgi et al., 2023; Coppola et al., 2024), developed and maintained at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste. The proposed spatial domain, shown in red in Figure 1 and referred to as **EURR-3**, has been designed to be sufficiently large to allow the model to develop its own internal climatology, while also encompassing regions from which large-scale dynamics are expected to influence local-scale processes (e.g., storm track positioning and mesoscale systems originating from the west and southwest).

A key requirement for the domain is that it be fully contained within the **Euro-CORDEX (EUR-11)** domain, from which boundary conditions for scenario simulations can be derived. Furthermore, it includes the previously adopted domain used in the convection-permitting ensemble simulations of the CORDEX-FPS Convection project (ALP-3), thereby enabling the estimation of inter-model uncertainty and providing a benchmark for comparison with the new simulations produced במסגרת H-ResIT.

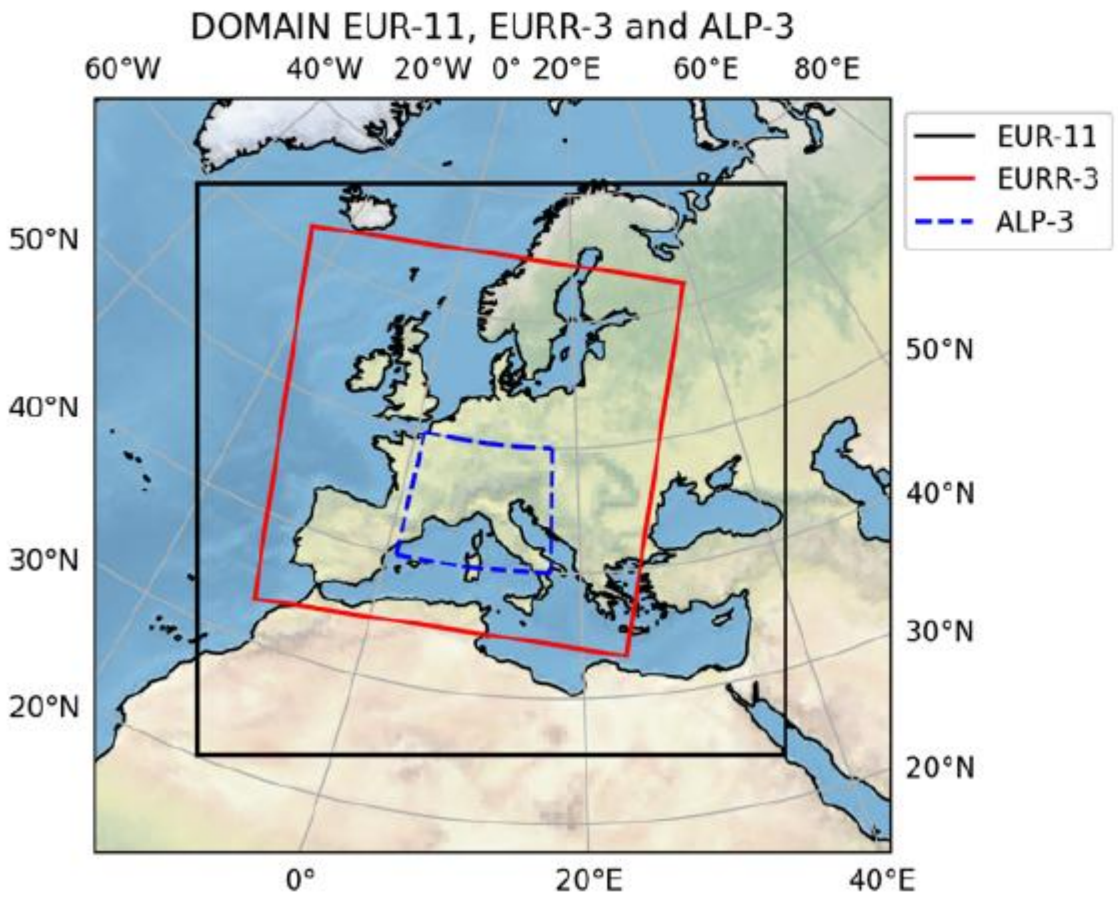

Figure 1. Domain of the simulations in red. Domain of Euro-CORDEX in black and domain ALP-3 used in CORDEX-FPS.

The set of output variables and their temporal resolution (summarized in Table 1) has been designed to provide input for hydrological and hydraulic models, as well as to support analyses of climate change impacts on phenomena such as storms (including both wind and liquid/solid precipitation).

Table 1: Example of output variables RegCM5-C with temporal frequency and units

Name	Frequency	Unit
Near surface temperature	1hr	K
Surface temperature	1hr	K
Daily maximum near-surface air temperature	Daily	K
Daily minimum near -surface air temperature	Daily	K
Wind components (u and v) at 50m, 100m and 150m	1hr	m/s
Near surface wind components (u and v)	1hr	m/s
Near surface wind speed	1hr	m/s
Daily maximum near-surface wind speed	Daily	m/s
Daily maximum near-surface wind speed of gust	Daily	m/s
Precipitation	1hr	$kg/m^2/s$
Daily maximum hourly precipitation rate	Daily	$kg/m^2/s$
Snowfall flux	1hr	$kg/m^2/s$
Surface air pressure	1hr	Pa
Sea level pressure	1hr	Pa
Near surface specific humidity	1hr	
Near surface relative humidity	1hr	%
Specific humidity at 50m	1hr	
Evaporation including sublimation and transpiration	1hr	$kg/m^2/s$
Potential evapotranspiration	1hr	$kg/m^2/s$
Surface upward latent heat flux	1hr	W/m^2
Surface upward sensible heat flux	1hr	W/m^2
Surface downwelling/upwelling longwave radiation	1hr	W/m^2
Surface downwelling/upwelling shortwave radiation	1hr	W/m^2
Total cloud cover	1hr	%
Boundary Layer Height	1hr	m
Low, Medium, High level clouds	1hr	%
Convective Available Potential Energy (CAPE)	1hr	J/kg

Computational Resources, Model Implementation, Configuration, and Optimization

Following a careful assessment of the computational and storage resources required to successfully complete the scientific data production phase—based on benchmarking using currently available computing systems—and, if necessary, the acquisition of additional resources, the following activities have been carried out:

- Implementation, configuration, and optimization of the ICTP RegCM5 regional climate model code on the selected high-performance computing (HPC) platforms, taking into account the specific hardware and software configurations in order to achieve optimal performance.
- Provision of technical support throughout the duration of the experiment, including troubleshooting issues encountered during the execution of climate simulations, as well as the setup and maintenance of all software required for data analysis and the production of scientific publications.
- Implementation of a **Data Management Plan (DMP)**, with particular attention to managing input and output data flows of the RegCM5 model. This includes addressing differences in storage capacity and access speed across computing systems, data transfer times, and the potential need for data replication across multiple systems to ensure timely achievement of scientific objectives.
- Development of software tools to enable data dissemination through internationally recognized sharing protocols (e.g., ESGF – Earth System Grid Federation).
- Design, implementation, and maintenance of long-term data storage solutions to ensure the availability of project outputs for community access and independent verification of results. This includes the publication of model code, computational environment details, and all tools used for generating graphical representations in scientific publications.

By using the EURR-3 domain described above, the RegCM5 convection-permitting configuration (RegCM5-CP) have been set up at approximately 3 km spatial resolution. The simulation used boundary conditions derived from **ERA5 reanalysis data** (Hersbach et al., 2020) and RegCM5 simulation over the Euro-CORDEX domain (EUR-11), which is itself driven by a **CMIP6 global climate model (GCM)** under a selected **Shared Socioeconomic Pathway (SSP)** scenario leading to a global warming level of approximately +4°C (e.g., EC-Earth3-Veg, MPI-ESM1-2-HR, NorESM2-MM).

Summary of simulation results

the RegCM5 model code was optimized and implemented, first on the HPC MARCONI computing platform at CINECA and subsequently on the LEONARDO platform. In parallel, a data management plan was developed to post-process the model output data in real time and prepare them in the appropriate format for final archiving, following the protocols required by the international community (ESGF archive).

The control simulation with the RegCM-CP model over the EURR-3 domain was completed at a resolution of about 3 km, using ERA5 reanalysis data as boundary conditions for the period 1999–2009, with the year 1999 used as a “spin-up.” The validation of the 10-year simulation has been completed, demonstrating the excellent quality of the produced data. The data have been post-processed and are ready in the format required by the ESGF archive protocols.

The RegCM5 simulation over the Euro-CORDEX domain at 0.11-degree resolution has also been completed, using the global model EC-Earth3-Veg—part of the CMIP6 experiment ensemble—as boundary conditions. This was then used as boundary conditions for the RegCM-CP simulation at approximately 3 km resolution over the EURR-3 domain.

The EURR-3 EC-Earth3-Veg simulation starts in 1994, used as a “spin-up” year, and has been completed for the following 20 years to cover the historical period. It also includes 10 years (2002–2011) centered around the 1.5°C global warming level (GWL) and 10 years centered around the 3°C GWL period (2048–2057).

The validation of the 20-year historical simulation has been completed, showing excellent data quality comparable to that of the control simulation.

A preliminary analysis of the climate change signal shows an increase in temperatures of up to 3°C during the summer season in the Mediterranean basin and during the winter season in Northern Europe. Extreme precipitation shows an increase across all regions, more pronounced in the Mediterranean basin. The data have been post-processed and are ready in the format required by ESGF archive protocols.

Here below we provide a brief extraction from the results for the sake of providing an example. Figure 2 presents seasonal biases (compared to OBS) in mean daily precipitation and surface temperature for the evaluation period (2000-2009) and historical period (1996-2005).

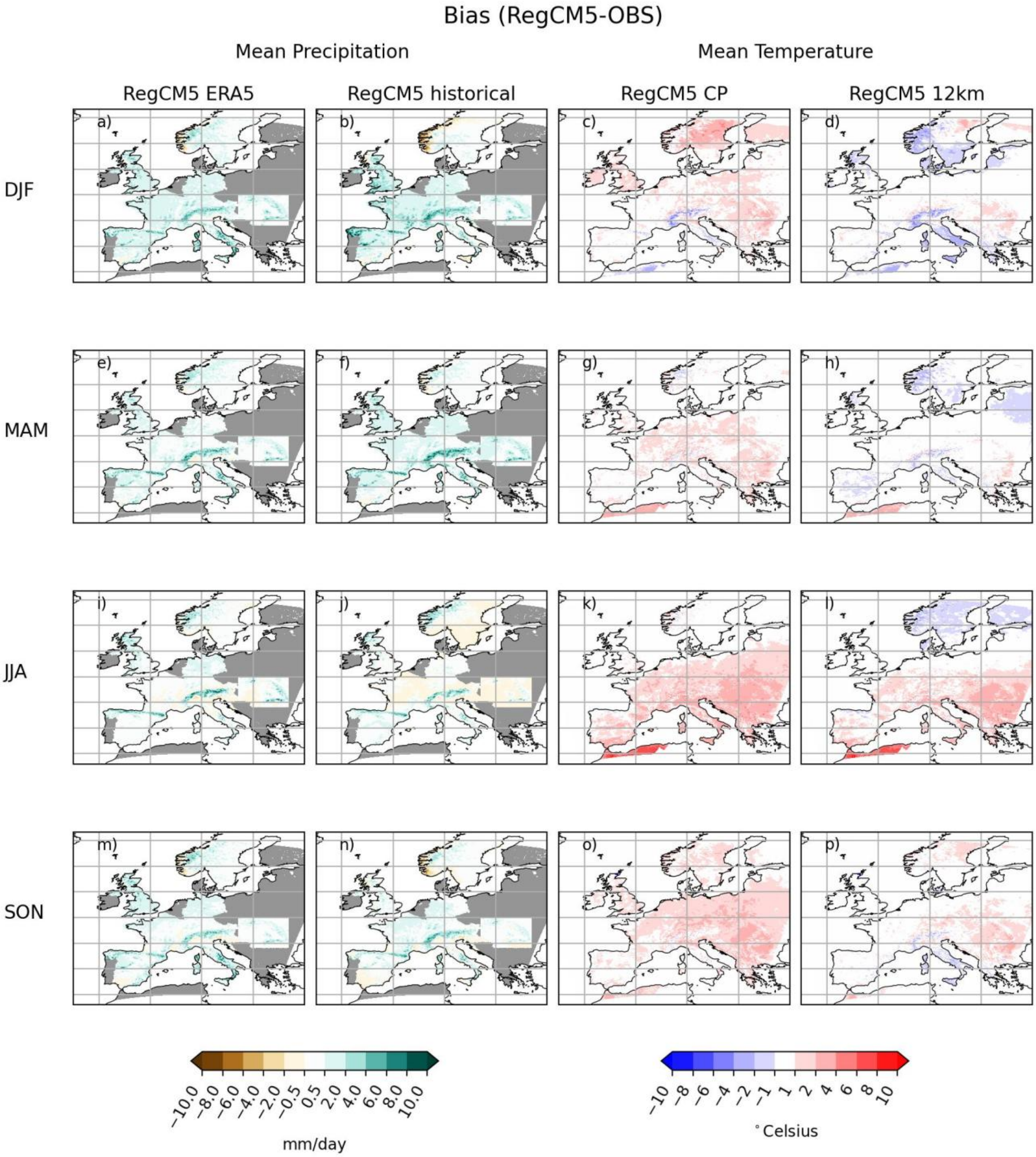

Figure 2: Seasonal biases (compared to OBS) in mean daily precipitation and surface temperature for the evaluation period (2000-2009) and historical period (1996-2005).

Figure 3 presents daily precipitation PDFs for 10 regions within the simulated domain for observations (2000-2009), evaluation period (2000-2009), historical simulation (1995-2005), GLW3 scenario (2048-2053).

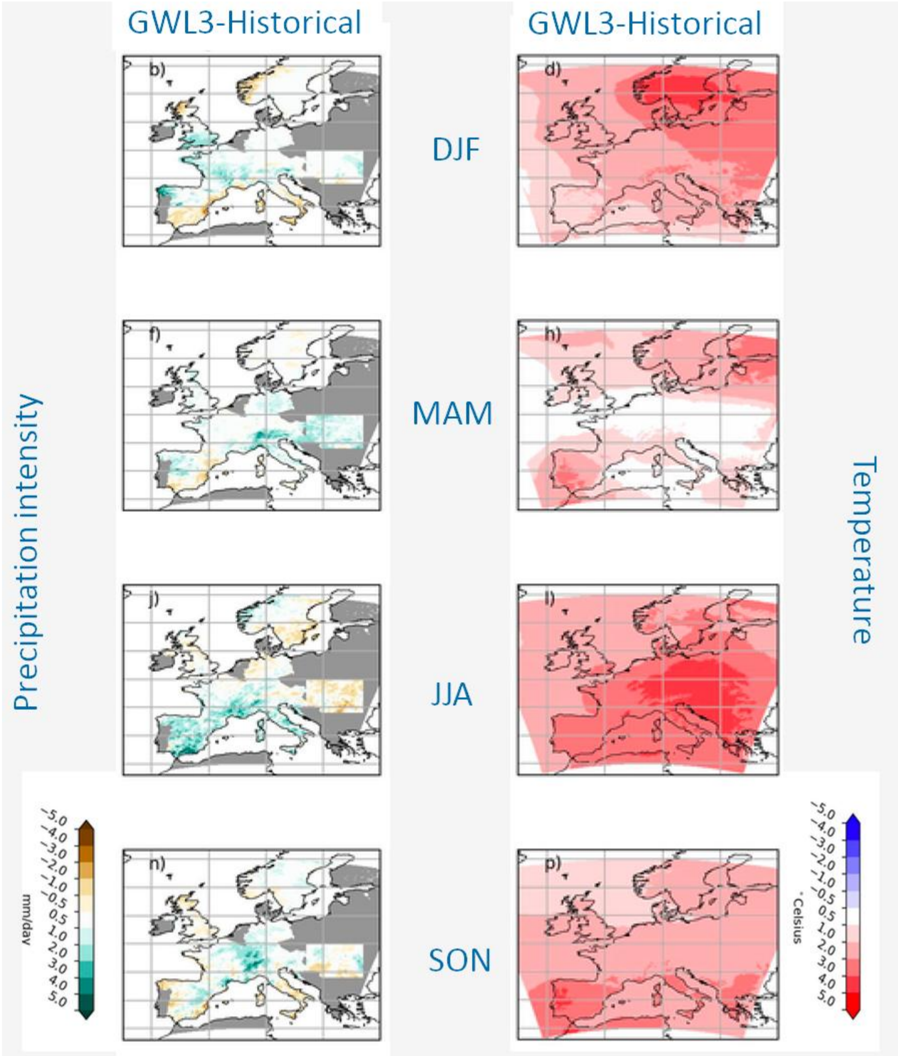

Figure 3: presents daily precipitation PDFs for 10 regions within the simulated domain for observations (2000-2009), evaluation period (2000-2009), historical simulation (1995-2005), GLW3 scenario (2048-2053).

Figure 4 shows seasonal differences in daily precipitation intensity and surface temperature between the historical simulation (1995-2005) and the GWL3 simulation (2048-2053).

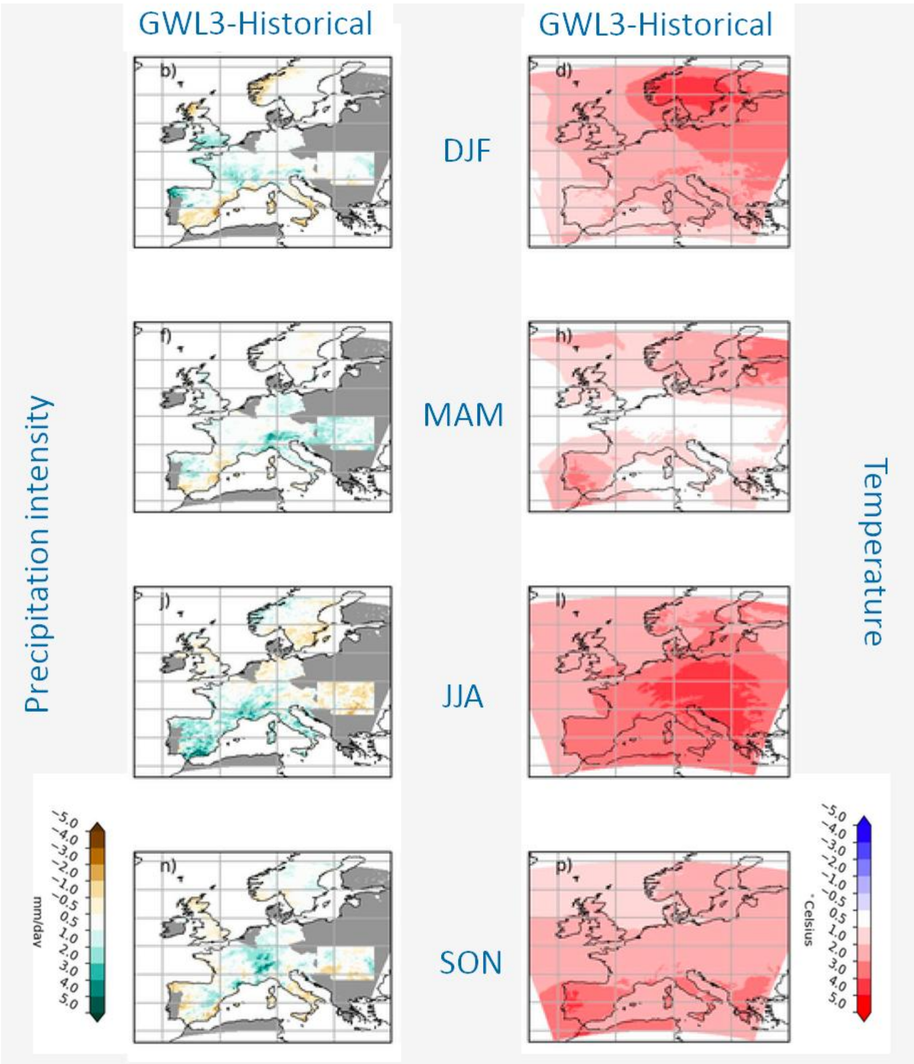

Figure 4. seasonal differences in daily precipitation intensity and surface temperature between the historical simulation (1995-2005) and the GWL3 simulation (2048-2053).

Figure 5 presents Seasonal differences in daily precipitation intensity and surface temperature between the historical simulation (1995-2005) and the GWL3 simulation (2048-2053).

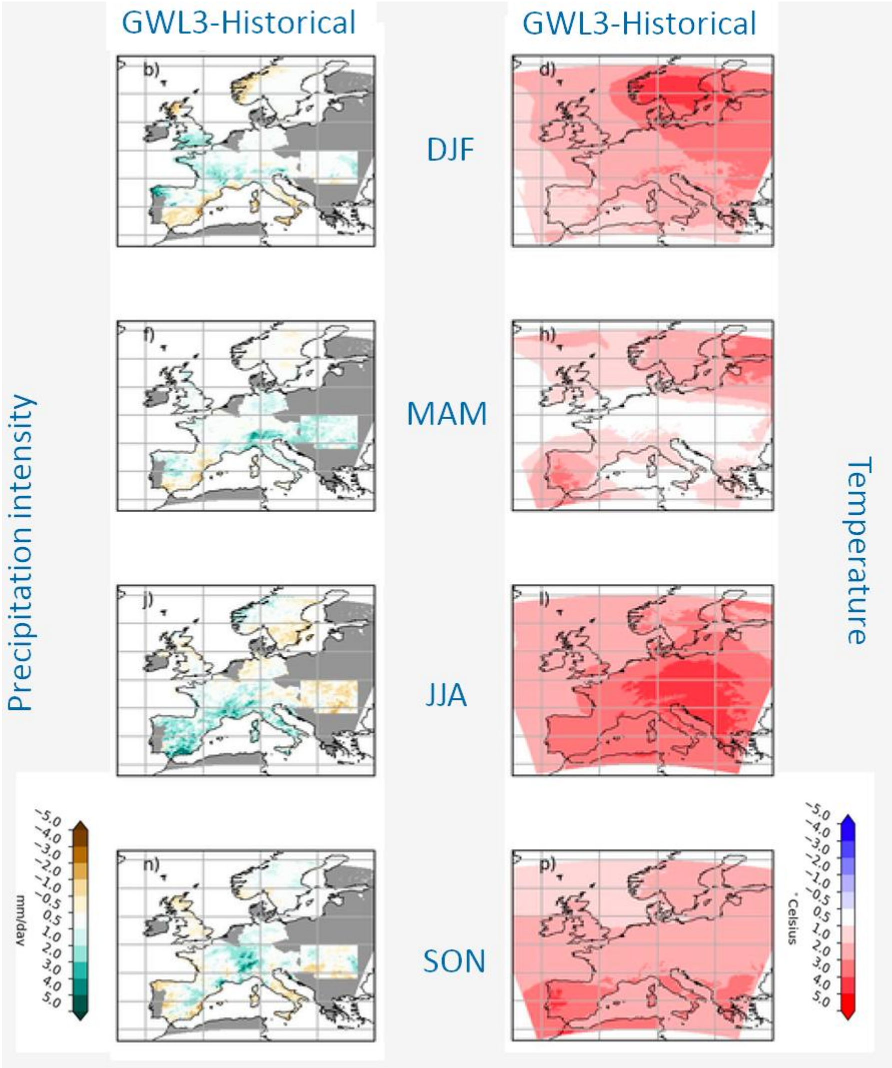

Figure 5. Seasonal differences in daily precipitation intensity and surface temperature between the historical simulation (1995-2005) and the GWL3 simulation (2048-2053)

Figure 6 presents a map of urban heat island effect for Italy.

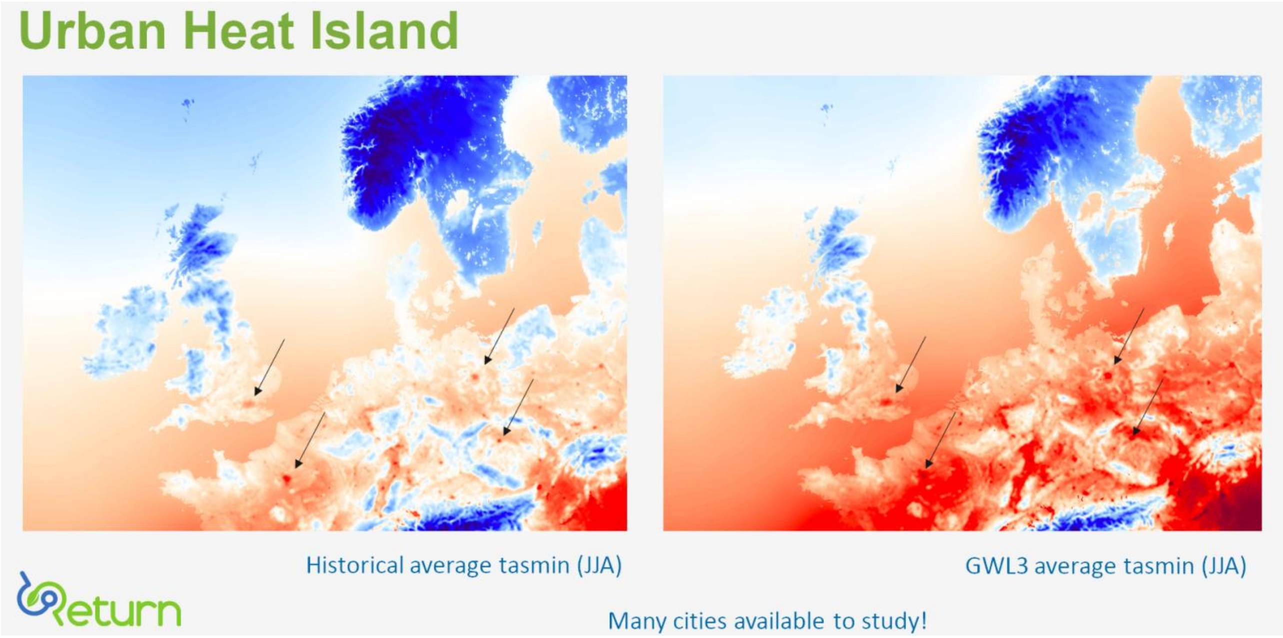

Figure 6: map of urban heat island effect for Italy.

Conclusions

The simulation herein developed and made available allow a refined interpretation of changes in climate that we may expect in the future over Italy. These data are an unprecedented information allowing to estimate future probability of extremes and therefore risk at the regional and very local level.

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