Project: **1481**

Project title: **Climate-Resilient Development Pathways in Metropolitan Regions of Europe – CARMINE**

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1. Brief overview of the project results acquired until now

To bridge the spatial scale mismatch between global climate datasets and regional risk assessments, climate information—spanning historical conditions and mid-term future projections—must be dynamically downscaled from coarse to fine resolutions. This downscaling process investigates non-linear spatial dependencies among multiple climate variables in the historical record and transfers this knowledge to generate high-resolution projections for future periods. Addressing existing gaps and uncertainties in regional climate risk information requires systematic correction of model biases. Accordingly, CARMINE develops and applies advanced spatiotemporal bias-correction and downscaling techniques based on artificial intelligence, including deep learning and reinforcement learning architectures, trained on Regional Climate Model (RCM) simulations and high-quality observational reference datasets.

The resulting bias-adjusted, high-resolution datasets enable robust detection and quantification of climate-related extreme events relevant to economic sectors and societal well-being. Using a consistent machine-learning architecture, the system captures the statistical characteristics of model outputs for bias correction, ensuring that climate variables are optimally adjusted to metropolitan-scale resolutions of approximately 1 km.

2. Modelling framework developed

During this reporting year, a comprehensive framework was developed to identify key climate hazards, evaluate their impacts using established indices, and build the foundation for actionable risk modelling and scenario generation in subsequent stages of the project. The analysis covers eight Case Study Areas (CSAs)—Prague, Leipzig, Funen–Odense, Athens, Barcelona, Bologna, Brașov, and Birmingham—which represent diverse climatic, environmental, and socio-economic contexts across Europe. These CSAs serve as testbeds for the evaluation and refinement of multi-hazard risk assessment methodologies and modelling tools.

The first component provides an overview of the eight CSAs, summarising their demographic, topographic, land-use, and socio-economic characteristics, which form the basis for understanding spatial variability in exposure and vulnerability to climate-related hazards. The climatic analysis relies on daily maximum temperature data from the EMO-1 dataset (Gomes et al., 2025).

Subsequently, the study examines the main climate hazards affecting the CSAs during the period 1990–2022, focusing on heatwaves, droughts, and extreme wet conditions. The assessment of heat-related hazards employs indices such as the Heat Magnitude Day (HMD) index (Zampieri et al., 2017) and the Heat Wave Magnitude Index daily (HWMId) (Russo et al., 2015). Meteorological drought conditions are quantified using the Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010), which incorporates both precipitation and potential evapotranspiration (PET). The SPEI was computed on a monthly scale using the reference period 1992–2022. Values of SPEI-1 ≤ -1 indicate drought conditions, whereas SPEI-1 ≥ 1 correspond to wet conditions, reflecting deviations in the climatic water balance of one standard deviation from the long-term mean. The computation is based on daily precipitation and PET values, with PET estimated using the Penman–Monteith equation.

To establish links between climate hazards and their potential consequences, the framework introduces a suite of impact-relevant indices and metrics serving as proxies for risk exposure. These include the Combined Stress Index (CSI), HMD, SPEI, and other derived indicators that quantify the intensity, frequency, and spatial extent of hazardous conditions. The CSI is used to evaluate the cumulative impacts of multiple environmental stressors—including temperature extremes, precipitation deficits, and water availability—

by statistically integrating calibrated indicators of thermal and hydrological stress into a single composite metric. This provides a multidimensional representation of environmental stress conditions. To ensure comparability across variables and locations, all input metrics were standardised using z-scores.

A Principal Component Analysis (PCA) was subsequently conducted independently for each CSA. The first principal component captures the dominant mode of joint variability between heat and drought conditions. Additional indicators, such as the number of wet months, maximum wetness intensity, and compound event likelihoods, provide a multi-layered characterisation of hazard exposure.

The results reveal a general increase in the frequency, duration, and intensity of heatwaves across all CSAs, with particularly strong upward trends in Athens, Barcelona, and Bologna (Figure 1). Drought conditions also exhibit increasing severity in several CSAs, whereas extreme wet periods appear more sporadically distributed. In regions such as Brașov and Leipzig, compound events (e.g., concurrent hot–dry or cold–wet extremes) emerge as significant concerns due to their amplified socio-environmental impacts. The evaluation of indices at the CSA level enables the identification of local hotspots, areas of overlapping risks, and long-term shifts in event probabilities. Results highlight pronounced intra-CSA variability, suggesting that climatic risks are unevenly distributed even within individual metropolitan regions.

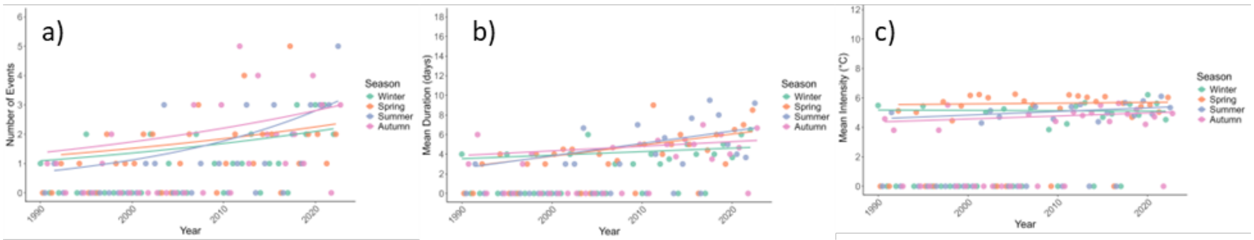

Figure 1. Analysis of heatwave a) occurrence, b) duration, and c) mean intensity for case study area of Barcelona.

At this stage of the project, partial dataset preparation has been completed, while a large amount of CPU and GPU node hours has expired. This discrepancy reflects a maternity leave and sudden personnel changes, the project's workflow that focused primarily on defining the analytical framework, collecting and preprocessing data, and establishing methodological and procedural foundations.

3. Summary and outlook

To date, this work has established the initial modelling framework for analysing and characterising climate hazards and their associated impacts across eight diverse European CSAs. The analysis focuses on three key hazards—heatwaves, droughts, and extreme wet conditions, over the period 1990–2022. Two primary indices were employed: the HMD index, which quantifies cumulative heat stress, and the SPEI, which measures meteorological drought severity. In addition, CSI, a statistical composite integrating HMD and SPEI through PCA provides a holistic assessment of compound events, such as concurrent heat and drought episodes. Preliminary results indicate a general increase in the frequency and intensity of heatwaves across all CSAs, accompanied by substantial intra-CSA variability in risk distribution. This framework establishes a solid foundation for the development of actionable risk modelling and climate adaptation scenarios in subsequent phases of the project. In the next stage, the framework will be tested and applied to climate projections for the period 2015–2050 derived from the EURO-CORDEX dataset for each CSA based on high resolved post-processed data.

4. References

Gomes et al. (2025). https://doi.org/10.2905/0BD84BE4-CEC8-4180-97A6-8B3ADAAC4D26

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