A CFD-based framework for urban extreme temperature mapping

A. Piazza[1,2], G. T. Bitsuamlak[3], M. Repetto[4], M. Burlando[5]

[1,4,5]University of Genoa, Genoa, Italy
[2,3]Western University, London, Ontario, Canada
[1]*alessia.piazza@edu.unige.it*, [2]*apiazz2@uwo.ca*, [3]*gbitsuam@uwo.ca*
[4]*maria.pia.repetto@unige.it* and [5]*massimiliano.burlando@unige.it*

SUMMARY
This study presents a combined statistical and numerical framework for mapping extreme temperatures in a complex urban environment. The municipality of Genoa, a coastal city in Italy, was used as a case-study example. Historical temperature data from 14 meteorological stations were analyzed using the Generalized Extreme Value (GEV) distribution to establish a statistical characterization of extreme temperatures across the city. A detailed digital twin of the city, incorporating topographic and land-cover information, was developed for conducting Computational Fluid Dynamics (CFD) simulations using OpenFOAM. RANS simulations were performed to reproduce the thermal conditions associated with extreme summer and winter events. The simulated temperature fields were validated against observations from the weather stations, showing good overall agreement. The resulting datasets were used to generate high-resolution maps of extreme maximum and minimum temperatures, highlighting the spatial variability temperatures within the city, that is seen to be locally affected by terrain features like topography and texture.

Keywords: CFD, Urban environments, extreme temperature

1. INTRODUCTION

Urban Heat Island (UHI) effect and heat waves are significant phenomena that affect urban environments, exacerbating the already elevated temperatures in cities and leading to an increase in illness and mortality. While the UHI effect phenomenon is one of the most prominent consequences of urbanization and climate change, heat waves are an extreme and unpredictable weather event that can have severe impact. For instance, the summer of 2003 saw an estimated 25,000 to 70,000 deaths across Europe attributed to heat waves. Particularly from June to September, pedestrian thermal comfort is significantly compromised due to extreme heat events. Therefore, understanding the complex spatio-temporal variation of temperature in a complex urban environment is vital to put mitigation measures in place and issue warnings, if needed, for general well-being of the public. As suggested by Mirzaei and Haghighat (2010) and further elaborated by Toparlar et al. (2017), two primary approaches can be used to study the UHI effect and urban temperatures more broadly: observational and simulation-based methods. The observational approach relies on measurement techniques, including urban temperature monitoring, that can be conducted through various methods, such as weather stations, mobile transverse, remote sensors and satellite imagery. These methods, although effective, present both spatial and temporal constraints. Simulation-based approaches, such as Computational Fluid Dynamics (CFD), can instead also explore potential future scenarios with high spatial resolution, thereby eliminating the spatial and temporal constraints of observation-based approaches.

While numerous studies have examined the temperature distribution in cities through satellite imagery or simplified empirical models, no studies to best of authors' knowledge have combined in-situ meteorological data with high-resolution CFD simulations across an entire urban area. The integration of these approaches provides a unique opportunity to produce realistic, spatially detailed, and physically consistent temperature maps that can support evidence-based climate adaptation strategies.

2. METHODOLOGY

Computational Fluid Dynamics (CFD) offers a unique opportunity to apply a physics-based interpolation of measured data through multi-physics simulations of the urban microclimate. The objective of this study is to create a framework to develop extreme temperature map at the city-scale using numerical simulations conducted on OpenFOAM. The city of Genoa in Italy, given its vulnerability to extreme heat events, has been selected as a case study for a proof of concept.

2.1. Genoa case study

Genoa, Italy, serves as an illustrative case of a coastal city that has experienced rapid growth and urban sprawl, resulting in significant modifications to its urban climate. Like many other coastal cities, Genoa is particularly vulnerable to the effects of climate change due to its proximity to the sea. Moreover, in this area the long-term data of the meteorological network of the Regional Agency for Environmental Protection (ARPAL) are available to establish a database of spatially distributed temperature parameters in different climatological scenarios within the city that can be used to set up physically representative CFD simulations.

2.2. Computational domain

The computational domain covers an area of 40 km × 20 km × 3 km, which is considered big enough to include the whole urban area of the city of Genoa, along with a surrounding area of several kilometers that is expected to cover the overall circulation induced by the UHI (Figure 1). The computational domain is bounded by a total of 7 patches that represent the sides (North, South, East and West), top, ground and sea boundaries of the domain.

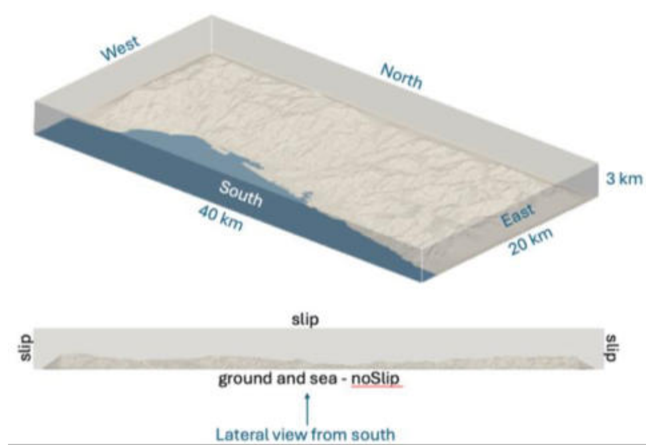

Figure 1. Computational domain

The ground boundary is characterized by the type of terrain (urban and rural area, that includes the hills around the city of Genoa). Cell sizes of 20 m and 10 m in the horizontal direction were used

for the sea and the terrain, respectively. Additional boundary layers for the terrain were used to ensure a finer refinement in the vertical direction close to the ground.
The urban texture within the scope of this study, in order to achieve computational feasibility, has been implicitly modeled using the subdivision of the land obtained from CORINE Land Cover (CLC) dataset. CLC offers a pan-European land cover and land use inventory with 44 thematic classes, ranging from broad forested areas to individual vineyards. This method, developed and introduced by Ricci and Burlando (2025), allows the automation and standardization of terrain subdivision process, without the need to rely on manual visual inspection. The patch information is extracted for the entire Municipality of Genoa and each patch is directly associated to a code depending on the land cover type and therefore to an aerodynamics roughness z_0. The values of z_0 defined based on the Davenport classification updated by Wieringa (1992), range from $z_0 = 0.004$ m for the sea up to $z_0 = 0.8$ m for discontinuous urban fabric, increasing with the degree of urbanization.

2.3.Boundary conditions and numerical settings

Simulations were performed to estimate the temperatures in the urban environment with boundary conditions corresponding to extreme events of risks of 50-year return periods. The computational domain is treated as a closed volume since the meteorological conditions corresponding to high (and low) extreme temperatures in Genoa occur during anticyclonic (advective) conditions, and they both correspond to low surface wind conditions. This also allows to avoid numerical instabilities, with no inlet or outlet patches defined. It is important to highlight that, in these conditions, the flow is buoyancy-driven and is therefore generated internally because of temperature gradients and the resulting density differences. The UHI effect was therefore reproduced by considering only sensible heat flux and anthropogenic heat sources at the ground, neglecting other components like evapotranspiration. Initial estimates for the heat fluxes in Mediterranean cities were derived from the literature. In particular, Mestayer et al. (2005) reported measurements of sensible heat flux in the city of Marseille (France) during summer days. These measurements were adopted as initial estimates for this study and subsequently adjusted iteratively to account for the specific urban characteristics and climatic conditions of Genoa. For the rural areas, mainly characterized by olive groves, agricultural fields and forests, a temperature lapse rate was applied, estimated from the extreme value analysis. The CFD simulations were performed using the open-source software OpenFOAM/v2312, employing a 3D steady-state RANS approach. The $k - \varepsilon$ turbulence model was utilized for the present study.

3. OUTCOMES

The results are analyzed for one return period, capturing the spatial variations in urban temperatures (Figure 2). Attention is given to the manifestation of the Urban Heat Island (UHI) effect, local hotspots, and the influence of topography and land cover on temperature distribution. Comparisons with observational data are provided where available to evaluate the accuracy of the simulations and the reliability of the generated heat maps. Two sets of simulations-one representing summer conditions (maximum temperatures) and the other representing winter conditions (minimum temperatures) were conducted for 1 return periods (50-year), resulting in a total of two simulation cases. Our results indicate that urban area results in higher temperatures for all the cases.

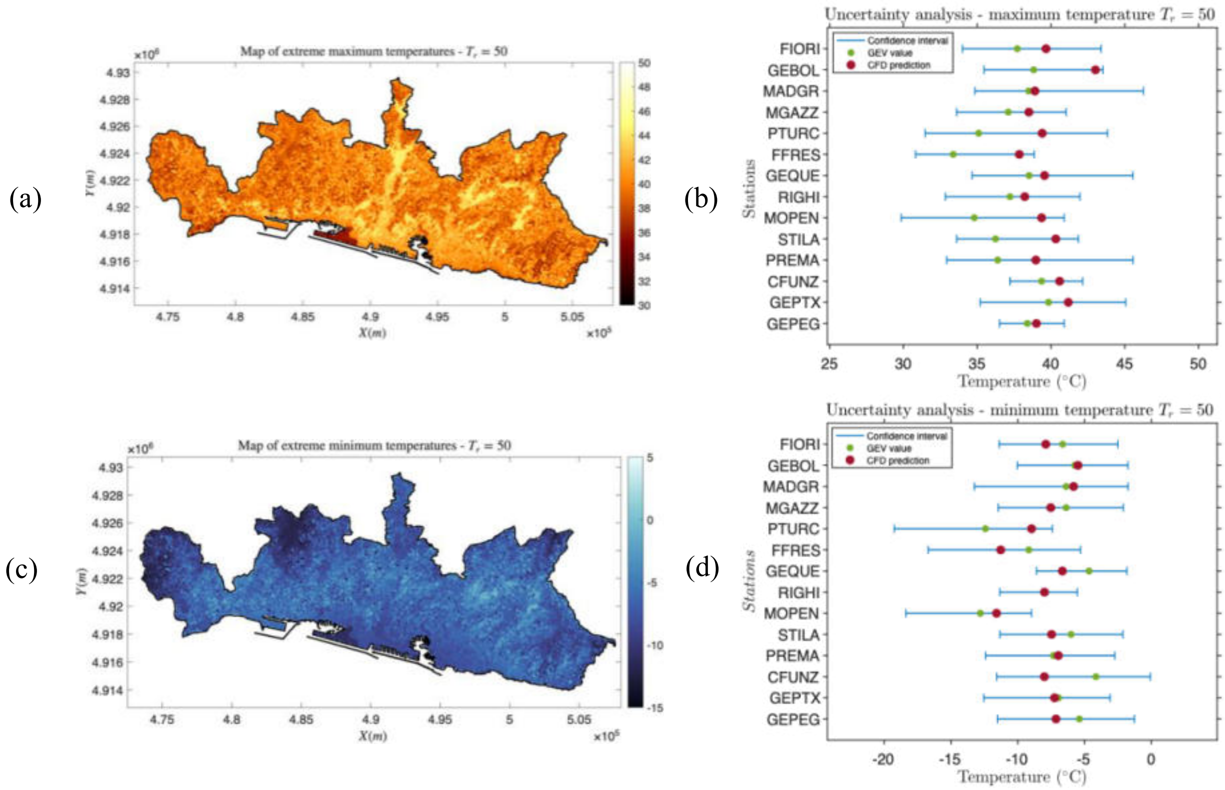

Figure 2. Contour maps of extreme temperatures for (a) maximum temperatures (50-year return period), (c) minimum temperatures (50-year return period). Comparison of CFD-simulated temperatures at meteorological stations with target extreme values. Error bars represent the 95% confidence interval of the target values (b) and (d).

4. CONCLUSIONS

The extreme maximum and minimum temperature maps for the Municipality of Genoa for a 50-year return period have been developed using CFD simulations and validated by comparison against values derived from extreme value analysis of field measurements. The results show a good agreement with the data obtained from the GEV analysis, suggesting the applicability of the framework to other return periods.

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