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CLIMATE RESILIENT STRATEGIES BY
ARCHETYPE-BASED URBAN ENERGY MODELLING

Methods for collecting and checking weather data

DELIVERABLE 2.1

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1. INTRODUCTION

1.1 Purpose

Global climate change leads to increased ambient temperatures, causing buildings to overheat and demand more energy while worsening indoor environmental quality. Urban Heat Island (*UHI*) effects, caused by local warming in urban areas, further exacerbate these challenges. Existing Urban Building Energy Modelling (*UBEM*) struggles to address *UHI* due to limited data on microscale climatic conditions and detailed mapping of urban areas. The CRiStAll project aims to address these gaps by creating detailed climatic datasets and exploring different urban configurations at the microscale.

Under the CRiStAll project, three interconnected research lines are developed. These include:

(A) building an urban climate model that incorporates the impacts of the Urban Heat Island (*UHI*) at the microscale, as well as the short-, mid-, and long-term (future weather data) consequences of climate change;

(B) putting the archetype-based Urban Building Energy Model (*UBEM*) into practice using typical urban environment configurations (street canyons);

(C) evaluating the impact of climate resilience and *UHI* reducing methods in urban locations.

Within work package 2, "Future urban climate model including *UHI*", which addresses research line A, a detailed urban climate model will be developed. It will incorporate the impacts of short-, mid-, and long-term climate changes (utilizing future weather data), as well as the micro-scale effects of the urban heat island (*UHI*). Task 2.1, "Methodology definition of *UHI* and collection of urban weather data", focuses on the collection and elaboration of weather data in order to allow the generation of a database of physical parameters to be used for correcting the bias errors of future weather data in the next steps of the project. In addition, a particular phase of this task is a systematic study to identify the best method to incorporate the *UHI* effect into the weather dataset.

1.2 Deliverable structure

This deliverable is structured into four sections, covering the collection and evaluation of urban weather data and the integration of the Urban Heat Island (*UHI*) effect into the weather dataset. Section 1 serves as the introduction, delineating the purpose (1.1), deliverable structure (1.2), and partner contributions to Task 2.1 development (1.3). Section 2 addresses the gathering and processing of weather data to establish a database of physical parameters for project use. Section 3 focuses on assessing weather data quality, detailing the methodology (3.1) and its application across different climate zones (3.2). Section 4 represents the final treated weather data, ready to be used for the next steps. Lastly, Section 5 emphasizes identifying the best method for incorporating the *UHI* effect into the weather dataset.

1.3 Contribution of partners

Polito led the task and wrote the deliverable with contributions from the partners involved. It also carried out the climate data collection and quality assessment for the city of Turin. Units obtained climate data for the locations of Bari and Rome. This research unit was also in charge of developing the methodology for climate data cleaning and gaps filling techniques. Unibz reviewed and described the *UWG* (Urban Weather Generator) tool for incorporating the urban heat island effect. All the partners reviewed and finalised the deliverable.

2. COLLECTION OF WEATHER DATA

In the CRiStAll project, analyses are performed for three localities in different Italian climatic zones. The selected cities are Bari from climatic zone “C” with HDD_{20} = 1185 K d, Rome from climatic “D” with HDD_{20} = 1415 K d, and Turin from climatic zone “E” with HDD_{20} = 2617 K d.

Data are gathered from both free field areas and urban environments at hourly time steps. The parameters collected include temperature, global horizontal solar irradiance, relative humidity, wind speed, and wind direction. The data collection period spans at least five years, focusing on the period prior to 2005. This timeframe aligns with the Representative Concentration Pathways scenarios utilized in CORDEX, where historical forcing is applied until 2005. Additionally, it should be noted that in certain instances, weather data after 2005 were incorporated based on availability, ensuring a comprehensive analysis of climatic trends. These data will be utilized for bias adjustment in the subsequent task (2.2) concerning future weather data.

2.1. Turin

For the city of Turin, the necessary datasets were sourced from ARPA Piemonte (Regional Environmental Protection Agency). Figure 1 presents the ARPA weather stations available in Turin province. A comprehensive review of accessible weather stations was conducted to assess parameter availability and time periods (Table 1). Based on this assessment, data were collected from the “Torino Buon Pastore” (urban environment) and “Bauducchi” (free field area) stations for ten years from 1994 to 2003.

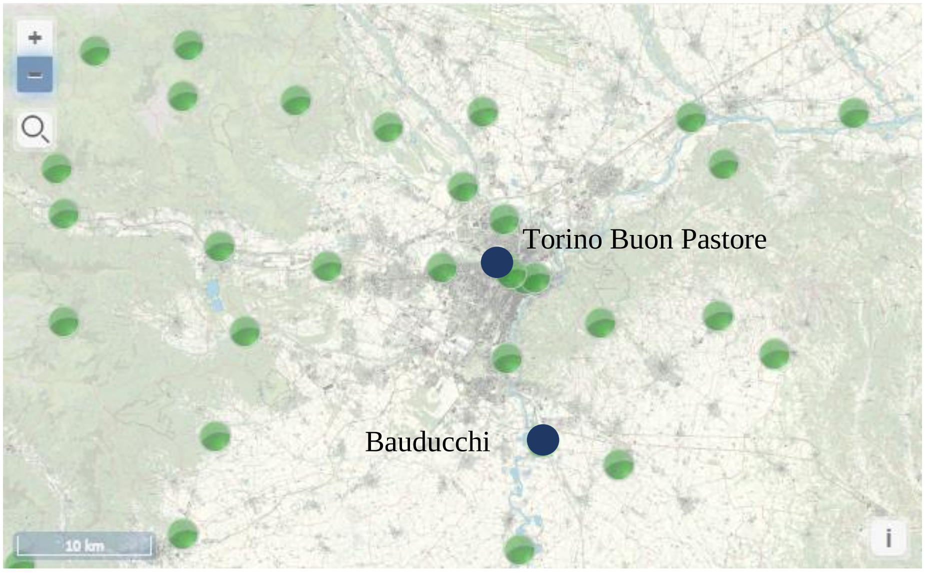

Figure 1: ARPA weather stations in the province of Turin

Table 1: List of accessible weather stations for the province of Turin

Station	Context	slm (m)	Temperature	Solar irradiance	Relative humidity	Wind speed	Wind direction
CASELLE	Airpot	300	From 2003	From 2003	From 2003	From 2003	From 2003
VENARIA CERONDA	Extra-urban	253	From 1997	-	-	-	-
TORINO REISS ROMOLI	Urban	270	From 2003	From 2003	From 2003	From 2003	From 2003
TORINO ALENIA	Urban	320	From 2005	From 2005	From 2005	From 2005	From 2005
TORINO BUON PASTORE	Urban	240	From 1989 to 2003	From 1989 to 2003	From 1989 to 2003	From 1989 to 2003	-
TORINO VIA DELLA CONSOLATA	Urban	290	From 2003	From 2003	From 2003	From 2003	From 2003
TORINO GIARDINI REALI	Urban	239	From 2004	From 2004	From 2004	-	-
TORINO ITALGAS	Urban	240	From 1992 to 2001	From 1992 to 2001	From 1992 to 2001	-	-
TORINO VALLERE	Extra-urban	239	From 2001	-	From 2001	-	-
PINO TORINESE	Extra-urban	619	From1988	From 1988	From 1988	From 1988	From 1988
BAUDUCCHI	Extra-urban	226	From 1993	From 1993	From 1993	From 1993	From 1993

2.2. Bari

For the city of Bari, weather data comes from different sources. The web GIS service of ARPA Puglia allows the extraction of weather data collected from weather stations across the regional territory. The service can be reached using the link

http://www.webgis.arpa.puglia.it/lizmap/index.php/view/map/?repository=1&project=meteo

Figure 2 presents the location of the available weather stations. Figure 3 points to the area around the city of Bari, where two locations could be identified: Bari Corso Trieste and Bari Carbonara. The stations provide all the data required for the present research, such as temperature, relative humidity, global horizontal solar radiation, wind direction, and velocity. Data are available every 30 minutes from 2010 to 2024. Both stations are related to locations in an urbanized area but with different building densities.

Additional weather data can be obtained from the Meteosat interface, https://meteostat.net/it/, with hourly weather data from 1953 to 2024 for Bari Palese and from 2005 to 2023 for Bari Carbonara. However, no global radiation data are available; nevertheless, the data of Bari Palese are of particular importance because the station is in a peripheral area near an airfield. To complete the dataset, radiation data could be recovered from other sources, such as services that use satellite data to record this parameter.

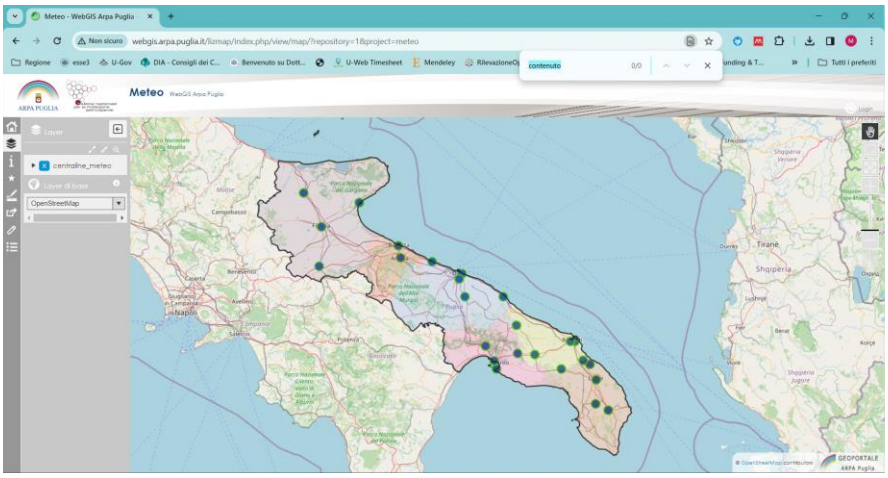

Figure 2: Stations of meteo Puglia

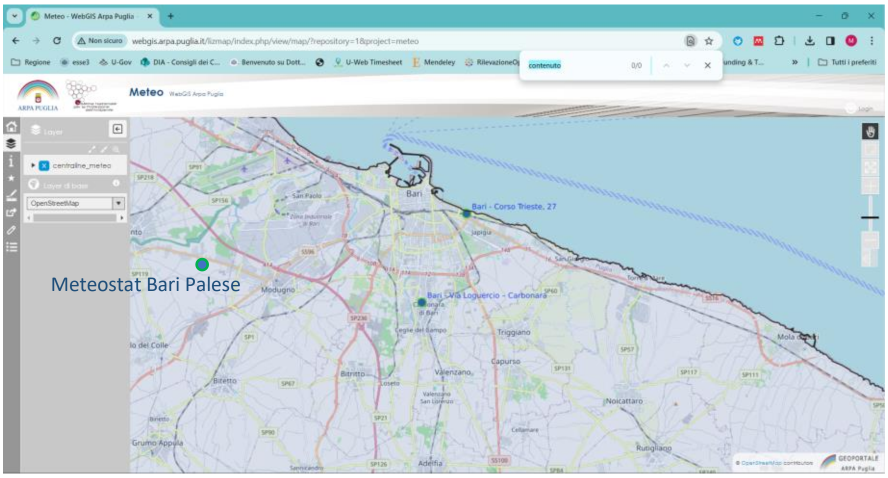

Figure 3: Weather stations in the area of Bari

2.3. Rome

The Rete Micrometereologica of the Lazio Region Provides data for the city of Rome,

https://www.arpalazio.it/web/guest/ambiente/aria/sistema-di-monitoraggio.

Nine stations have data available for download, and the time span is from 2013 to 2023. Table 2 reports the information about the stations, with highlighted those for the area around Rome. Weather stations with codes AL001, AL003, and AL004 on the outskirts of Rome and AL007 located in the city center have been used for this research. Figure 4 shows the location of the considered weather stations on the map.

Table 2: Weather stations of the Rete micrometeorological of Regione Lazio

Station	Code	City	Latitude	Longitude	height
Tor Vergata	AL001	Roma	41.84153	12.64792	104
Latina	AL002	Latina	41.485	12.84555	25
Cavaliere	AL003	Roma	41.92889	12.65832	57
Castel di Guido	AL004	Roma	41.88942	12.2665	61
Istituto Jucci	AL005	Rieti	42.42192	12.81172	379
Aeroporto militare Frosinone	AL006	Frosinone	41.64012	13.29754	178
Boncompagni	AL007	Roma	41.9096	12.49657	72
Aeroporto militare Viterbo	AL008	Viterbo	42.42887	12.05653	297
Ceprano	AL009	Ceprano	41.543958	13.483648	111

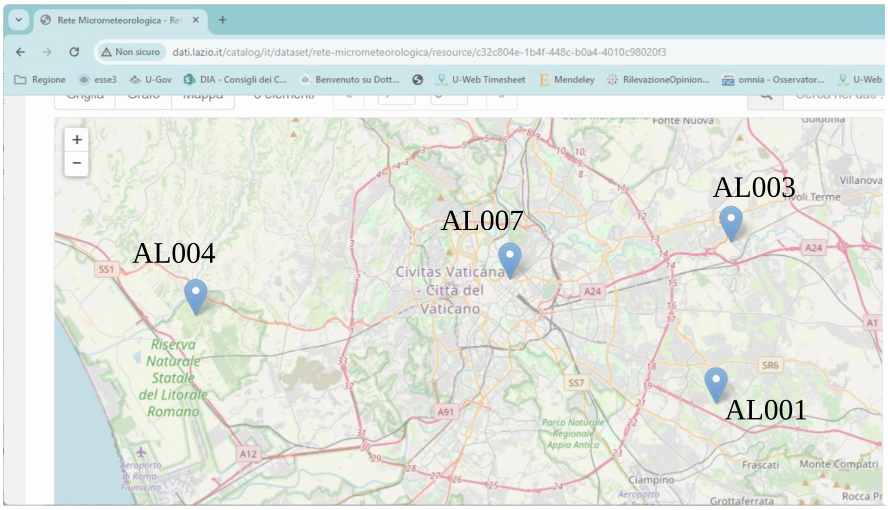

Figure 4: Considered weather stations for Rome

3. QUALITY ASSESSMENT OF WEATHER DATA

3.1. Methodology

The observational weather data are not immediately usable due to missing values, corrupted values, and values outside the plausible range, e.g., relative humidity greater than 100 %. These issues may arise from specific weather conditions, errors in recording and post-processing the data, and loss of recorded data due to the lack of power supply. To obtain a solid and computable data set of values for energy analysis, a data quality treatment should be performed on the raw data obtained from weather stations in order to:

- Check the continuity of the date and time range,
- Find missing values and interpolate them
- Find values outside the plausible range and correct them.

The first step is correcting syntax and writing errors. After this step, the dataset will be treated through the imposition of four quality rules to identify valid days for the calculation (Pezzi, A. et al., 2023). The following four rules are to be fulfilled for a day to be considered valid.

- <u>Rule A</u>: every climatic parameter has to be valid for at least 18 hours during the day. This has to be satisfied in order to have consistent data to be used in the computation and avoid the presence of too many gaps to be filled with interpolation in the following steps.
- <u>Rule B</u>: the first and last values of the whole dataset have to be valid for all parameters; if not, the first and/or last day of the set have to be considered invalid. This condition is necessary because if interpolation of values is to be taken on the first/last day, valid data may be required in the first/last hour to compute the interpolated values.
- <u>Rule C</u>: for every climatic parameter, a maximum of 6 consecutive hours of invalid data is acceptable across two contiguous days. This limitation aims to avoid the problem of interpolating data across too long time intervals, such as near stocks of 5+5 hours of invalid values.

- Rule D: solar radiation values have to be valid during all hours between sunrise and sunset. This rule is the most restrictive one because if solar radiation is invalid in just one hour, the whole day is to be considered unacceptable. This is due to the fact that data gaps are filled through linear interpolation. However, if this approach is consistent for parameters like temperature and relative humidity, it cannot be extended to solar radiation because the latter does not vary on linear bases. Additional efforts are ongoing to overcome this problem.

The research is going on with additional efforts to increase the number of valid data available in the dataset to obtain improved reference data. For gaps greater than six hours and up to 24 hours, linear interpolation is adopted using previous and forthcoming 24-hour data if present in the dataset. For larger gaps up to 48 hours, instead, a SARIMA approximation is under testing. This approximation is able to replicate the general trend of a time series, improving the database that recovers climate data. In the case of missing radiation data, a similar approach is under development: a linear interpolation is performed on the k_t value, i.e., the ratio between the radiation on the ground and at the exterior of the atmosphere since this parameter has a more linear variation than the global radiation. This approach has been successfully used in literature.

3.2. Application

The methodology was implemented by developing a Python script (Figure 5). After initial validation and filtering out the invalid parameters, by applying the four mentioned rules and conducting linear interpolation of the valid data for the three Italian locations, a pool of valid data for each location was obtained.

```python
def CTI_database_treatment(pathDATA,dataset,dataset2,Result_F1,Result_F2a,
                           Result_F2b):
    print('#-------------------------------------------#')
    print('# STARTING FUNCTION: F2_CTI_database_treatment #')
    print('#-------------------------------------------#')
    # 0 - IMPORTING LIBRARIES ================================================
    import time
    start = time.time()
    import numpy as np
    import pandas as pd
    import pickle
    import pvlib as pv


    # 1 - MODEL PREPARATION ==================================================
    with open(pathDATA+Result_F1, 'rb') as input:
        df = pickle.load(input)
    # number of stations
    nstat=len(df)
    results = [dataset2]*nstat
    #This list is needed to output treated data.
    stat_prov, stat_days = [],[]
    stat_nA, stat_nB, stat_nC, stat_nD, stat_nE = ([] for _ in range(5))
    stat_remaining_days = []
    interp_tmp, interp_rhu, interp_vel = ([] for _ in range(3))
    #These lists are to output data treatment statistics.
    # first check the data.ora column, unfortunately some files use a different format so this format
    # needs to be transformed possible format are "%d/%m/%Y %H:%M" transform in  "%Y-%m-%d %H:%M:%S"
    timefmt1="%d/%m/%Y %H:%M"
    timefmt2="%Y-%m-%d %H:%M"
    # 2 - DATA LOADING AND FIRST VALIDITY CHECK ==============================

    # if the station name is nan, MT for this case don't proceed with operation
    # the chack has been erased, no matera in database
#    for nr_db in [x for x in range (0,nstat) if not pd.isnull(df[x].name)]:
    for nr_db in [x for x in range (0,nstat)]:
        print('Analyzing province '+str(nr_db)+' out of ', nstat)
        # check the format of data.ora
        if "/" in df[nr_db].dataframe["data.ora"][0]:
            #transform in a series of strings with the correct format. I use strftime to transform in string datehour object
            # this has been done to avoid "possible" problems in the following passages. maybe it could work with datetime object as well
            df[nr_db].dataframe["data.ora"]=pd.to_datetime(df[nr_db].dataframe["data.ora"],format=timefmt1).dt.strftime(timefmt2)
        alt = df[nr_db].alt
        lat = df[nr_db].lat
        lon = df[nr_db].lon
        province = df[nr_db].name
        #Extracting from the database the parameters of CTI station.
```

Figure 5: A part of the developed Python script

4. FINAL WEATHER DATA

For the three selected Italian cities (Turin, Bari, and Rome), processed weather data that can be utilised to rectify the bias errors in future weather data during the subsequent stages of the project have been created. As an example, in this Section, the results for the city of Turin are summarised.

On an hourly basis, the annual averages over ten years (from 1994 to 2003) of temperature, global solar irradiance, relative humidity, and wind speed are presented for "Torino Buon Pastore" (urban environment) and for "Bauducchi" (free field area) stations of Turin from Figure 6 to Figure 9, respectively. Comparing weather data from an inside-city station with an outside-city station can provide valuable insights into several aspects, including the urban heat island effect.

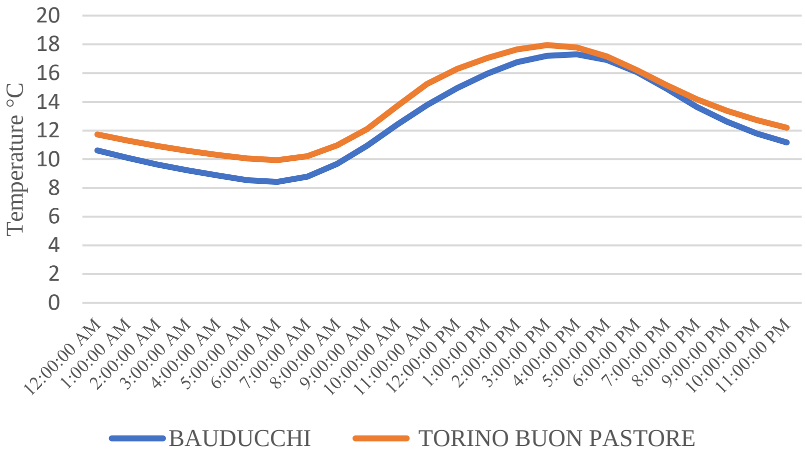

Figure 6: Annual mean of the external temperature (1994-2003), on an hourly basis, for two stations of Turin

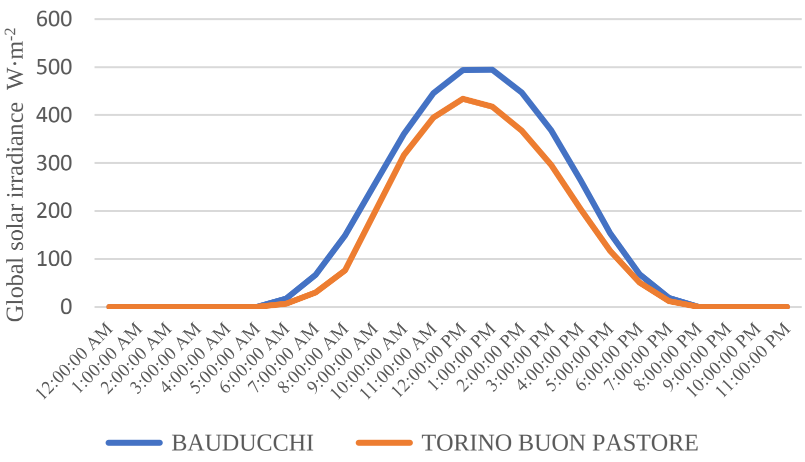

Figure 7: Annual mean of the global horizontal solar irradiance (1994-2003), on an hourly basis, for two stations of Turin

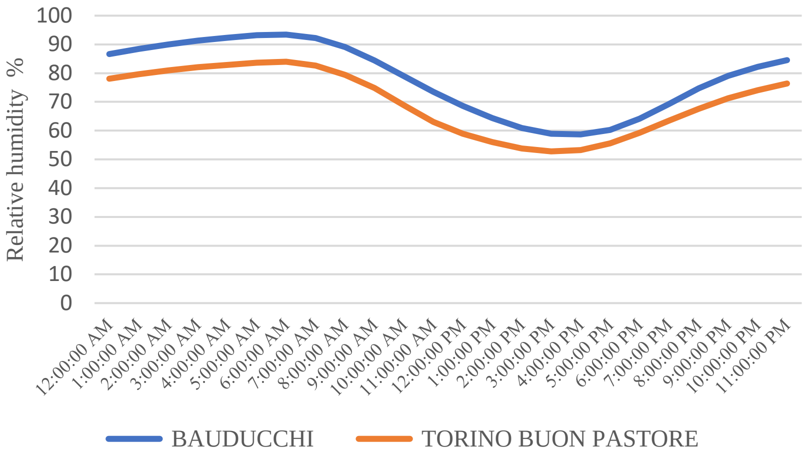

Figure 8: Annual mean of the relative humidity (1994-2003), on an hourly basis, for two stations of Turin

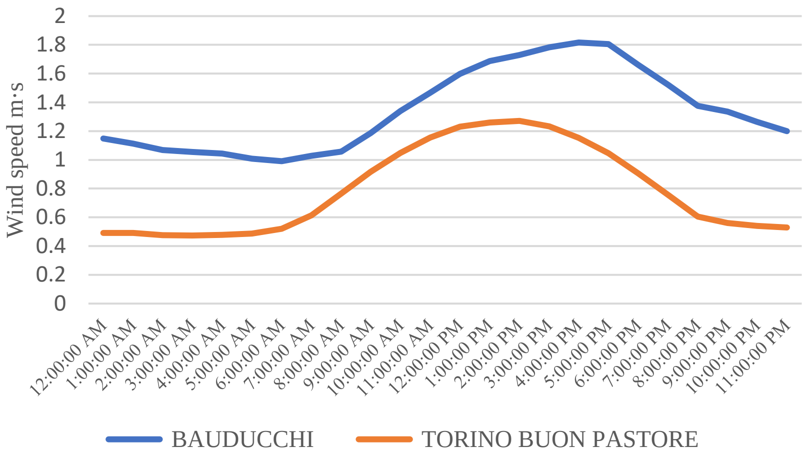

Figure 9: Annual mean of the wind speed (1994-2003), on an hourly basis, for two stations of Turin

Urban areas experience higher temperatures (Figure 6) due to human activities, such as buildings, roads, and industrial processes, which absorb and trap heat. For solar irradiance, differences can reveal the influence of various factors, including urban morphology, atmospheric conditions, and geographical location. In the case of Turin (Figure 7), the decrease in global solar irradiance might be due to microclimate effects such as obstructions and air pollution. For relative humidity, urban areas experience lower levels (Figure 8) compared to free-filed areas due to increased heat and surface evaporation. A much greater difference in wind speed is observed between the two stations (Figure 9). Due to fewer obstructions, less surface friction, and more even airflow, wind speeds are typically higher in free-field areas than in urban settings. However, interaction of urban morphology, land use patterns, topography, and meteorological phenomena can lead to complex wind speed patterns.

5. INCORPORATING URBAN HEAT ISLAND EFFECT

Some tools and methodologies already available in the literature can be used to incorporate the Urban Heat Island effect in urban scale simulation. Among them, the *Urban Weather Generator UWG* by MIT (https://urbanmicroclimate.scripts.mit.edu/uwg.php) was found to be one of the most popular, with several examples in the scientific literature.

Specifically, from an overview of journal papers about urban microclimate published in the last 10 years and indexed in the Scopus database, 38 of them adopted *UWG* as a modelling tool. As a whole, considering these researches only, *UWG* was employed to study the urban climate conditions in 34 different cities and, in some cases, for different neighborhoods of the same urban settlement. Out of these 38 researches, examples of applications were often found in Italy (Rome, Catania), China (Hangzhou, Guangzhou, Nanjing, Nanning, Tianjin, Shenzhen), France (La Rochelle, Lyon, Nantes, Paris, Toulouse), Spain (Barcelona, Pamplona), as reported in Figure 10.

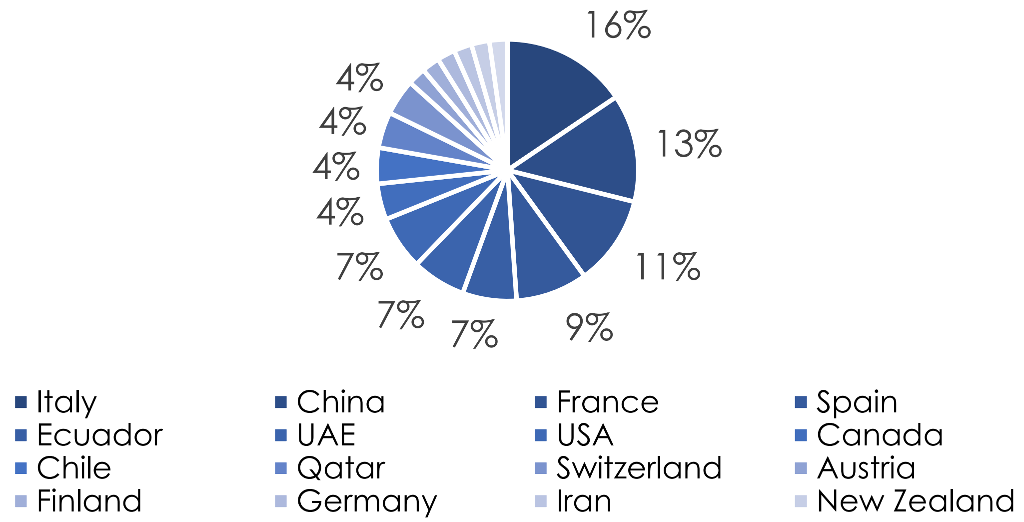

Figure 10: Countries of locations most frequently found in the considered literature applying UWG

The general trend of selected research adopting the *UWG* shows a positive growth. Starting from 2020, the number of published papers per year has been at least 5/year, with a recent peak of 9 in 2023, demonstrating an increased diffusion of this tool in the framework of the characterization of urban microclimates.

As regards the *UWG* modelling, it integrates several meteorological parameters with urban morphology and site features, giving particular relevance to urban geometry. As shown in Figure 11, it is based on four different models: (1) the *rural station model*, (2) the *vertical diffusion model*, (3) the *urban boundary-layer model*, and (4) the *urban canopy (UC) and building energy model (BEM)*. The *rural station model* reads the data collected by a rural weather station and performs an energy balance at the soil surface through finite difference modelling. The calculated rural sensible heat flux and the collected weather data of air velocity and temperature are then used in the *vertical diffusion model* to calculate the vertical air temperature profile above the rural weather station. The rural sensible heat flux and the vertical air temperature profile are considered as inputs in the *urban boundary-layer model*, together with urban sensible heat fluxes calculated by the *UC-BEM*, in order to perform an energy balance and estimate the air temperature above the urban canopy layer. Finally, the *UC-BEM* is able to derive the urban air temperature and humidity at street level, assuming that the air inside the considered street canyon is well-mixed. As regards humidity, it is determined by solving a latent balance under the hypothesis that the humidity in the urban canopy layer is the same as the weather station.

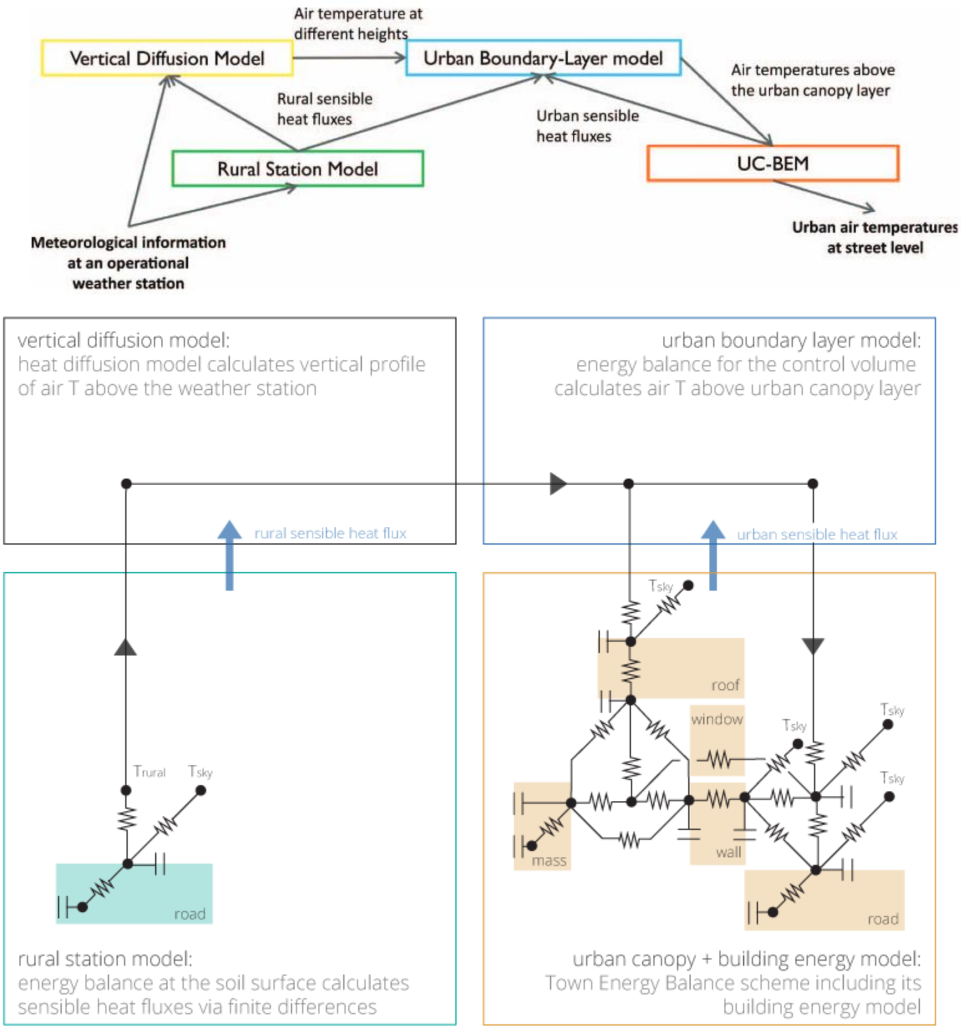

Figure 11: The four models part of the UWG. Figures are taken from Bueno et al., 2013 (top figure) and from the UWG website (https://urbanmicroclimate.scripts.mit.edu/uwg.php) (bottom figure).

Considering both the diffusion of the *UWG* and its technical features, it has been considered as a tool to adopt in the framework of the project in order to include *UHI* effects in *UBEM* simulations. In particular, on the one hand, the presence of an already rich literature based on applications of this tool will allow for easier and more robust comparisons and, on the other hand, the included modelling techniques and approaches are considered adequate and suitable not only for the characterization of the *UHI* effects but also to contribute to the assessment of the efficacy of different mitigation measures to analyze and discuss in the most advanced phases of the project. Finally, *UWG* is an open-source tool, an aspect that will facilitate the future adoption of the CRiStAll methodology by the NAGE members as well as other external stakeholders.

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