Using WRF-UCM as Boundary Forcing for Microscale Models in Data-Scarce Urban Environments

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Abstract

Urban microclimate models are widely used to analyse urban heat island effects and thermal conditions at fine spatial scales. However, microscale models such as ENVI-met require detailed meteorological forcing data, which are often unavailable or insufficient in many urban environments, particularly in smaller cities or regions with sparse meteorological observation networks. This study presents a multi-scale modelling approach that uses outputs from the open-source Weather Research and Forecasting model coupled with an Urban Canopy Model (WRF-UCM) to generate forcing data for ENVI-met simulations. ERA5 reanalysis data and nested WRF-UCM domains are used to simulate meteorological conditions over Košice (Slovakia), and selected atmospheric variables are extracted and converted into meteorological forcing data for microscale ENVI-met simulations. Results demonstrate that WRF-UCM-derived forcing data can reproduce realistic temporal variability in key atmospheric parameters. Validation against observations showed that ENVI-met simulations forced by WRF-UCM improved mean absolute errors by 8.4% for air temperature, 6.8% for relative humidity, and 25.1% for wind speed compared with WRF-UCM alone. The proposed approach enables the application of microscale urban climate models in data-scarce environments while preserving physically consistent initial and boundary conditions. It also improves the representation of regional atmospheric influences, supporting more robust and transferable urban climate analyses.

1. Introduction

Urban climate modeling plays an increasingly important role in understanding the interactions between atmospheric processes, urban morphology, and anthropogenic influences. Accurate simulation of urban meteorological conditions is essential for applications such as heat stress assessment, air quality analysis, renewable energy planning, and climate adaptation strategies. While mesoscale numerical weather prediction models, such as the Weather Research and Forecasting (WRF) model coupled with Urban Canopy Models (UCMs), can capture large-scale atmospheric dynamics and represent urban land-surface processes (Martilli et al., 2002; Chen et al., 2011; Fedor and Hofierka, 2022), they often lack the spatial resolution required to resolve microscale phenomena within complex urban environments.

Microscale models, including computational fluid dynamics (CFD) approaches and high-resolution urban climate models such as ENVI-met, provide a more detailed representation of airflow, turbulence, radiation exchange, and thermal interactions at the street or neighbourhood scale (Bruse and Fleer, 1998; Toparlar et al., 2017). However, these models strongly depend on accurate boundary and initial conditions, which are commonly derived from observational networks or high-resolution meteorological datasets. In many regions, especially in smaller cities or developing areas, such observational data are sparse, incomplete, or entirely unavailable. This limitation significantly constrains the applicability and reliability of microscale urban simulations.

To address this challenge, mesoscale urban climate simulations can serve as an alternative source of boundary forcing for microscale models. The WRF model, enhanced with urban parameterizations such as the Single-Layer Urban Canopy Model (SLUCM) or Building Effect Parameterization (BEP), is capable of generating spatially and temporally continuous atmospheric fields that incorporate urban effects (Tewari et al., 2007; Salamanca et al., 2010; Chen et al., 2011). These outputs can potentially provide physically consistent forcing data for nested microscale simulations, even in data-scarce environments. Previous studies have demonstrated the benefits of coupling mesoscale atmospheric models with microscale urban climate models for improving the representation of local thermal conditions and urban environmental processes (Schubert and Grossman-Clarke, 2014). Such coupling approaches enable the integration of regional atmospheric forcing with detailed urban morphology and microscale surface–atmosphere interactions.

This paper investigates the use of WRF-UCM outputs as boundary forcing for microscale urban models in regions with limited observational infrastructure. The study focuses on evaluating the consistency, applicability, and limitations of this coupling approach under realistic urban conditions. Particular attention is given to the representation of near-surface meteorological variables relevant for urban-scale analyses, including wind speed, wind direction, air temperature, and humidity.

The presented workflow demonstrates how open-source atmospheric modeling tools can be combined to support urban climate studies in locations where dense measurement networks are unavailable (Grimmond et al., 2010; Oke et al., 2017). By leveraging WRF-UCM as an intermediate forcing layer, the proposed methodology aims to improve the accessibility of high-resolution urban environmental modeling and contribute to reproducible geospatial workflows within the open-source geospatial community. The novelty of this study lies in the

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development and evaluation of a reproducible workflow for generating ENVI-met forcing data directly from WRF-UCM outputs in data-scarce urban environments.

2. Study Area and Input Data

2.1 Study area

The study area is located in the city of Košice, situated in eastern Slovakia (Figure 1). Košice is the second largest city in the country and represents an important regional center characterized by a heterogeneous urban structure, mixed land use, and varying building densities. Due to its complex urban morphology and diverse surface characteristics, the city provides suitable conditions for investigating urban meteorological processes at both mesoscale and microscale levels.

Košice lies in the Košice Basin, surrounded by moderately elevated terrain that influences local atmospheric circulation patterns. The city experiences a temperate continental climate with warm summers and cold winters, while local meteorological conditions are additionally affected by topography, urban heat storage, and anthropogenic activities. Prevailing wind conditions are shaped by the orientation of the basin and nearby valleys, producing spatial variability in airflow and turbulence within the urban canopy.

The urban structure of Košice includes a combination of historical compact development in the city center, residential housing estates with mid- and high-rise apartment blocks, industrial zones, transportation infrastructure, and suburban areas with lower building density. This diversity creates varying aerodynamic roughness and thermal properties that are relevant for urban climate modeling. In particular, the coexistence of dense built-up districts and open areas with rugged surrounding orography makes the city suitable for evaluating the transition between mesoscale atmospheric forcing and microscale urban processes.

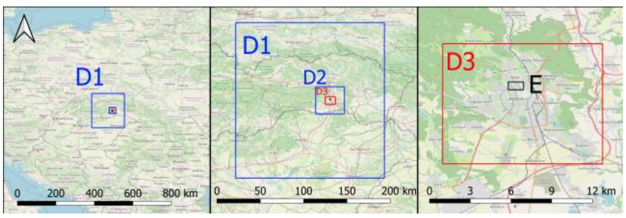

Figure 1. Study area including WRF (D1, D2, D3) and ENVI-met (E) domains.

From the perspective of data availability, Košice represents a typical medium-sized Central European city with limited high-density meteorological observations. Although standard meteorological stations are available, detailed urban measurement networks required for microscale model initialization and validation are sparse. This limitation motivates the use of WRF-UCM simulations as an alternative source of spatially continuous atmospheric boundary conditions.

The selected domain for microscale analysis focuses on representative urban districts characterized by different building configurations and land-use types. The area includes densely built residential blocks, transportation corridors, and open urban spaces that allow assessment of local airflow patterns and thermal variability under realistic urban conditions.

The selected simulation period represents a typical summer situation characterized by clear-sky conditions and weak synoptic forcing, allowing the influence of urban morphology on the local microclimate to be clearly expressed while still capturing mesoscale processes associated with nearby orography and convection (outflow boundary).

2.2 Input Data

The preparation of high-quality input data represents a crucial step in urban atmospheric modelling, particularly when coupling mesoscale and microscale simulations. In this study, the input datasets consisted of atmospheric forcing data generated by the WRF model coupled with an Urban Canopy Model (WRF-UCM), together with detailed geospatial data describing urban morphology, land cover, buildings, and vegetation within the study area.

The mesoscale atmospheric simulations were performed using the Weather Research and Forecasting (WRF) model parameterized with the Single-Layer Urban Canopy Model (SLUCM) (Tewari et al., 2007; Chen et al., 2011), following the methodology described in previous studies focused on the urban climate of Košice (Fedor and Hofierka, 2022). The WRF-UCM configuration employed nested computational domains with progressively increasing spatial resolution to capture both regional atmospheric circulation and local urban effects (Skamarock et al., 2019). The innermost domain covering the Košice urban area was configured at high spatial resolution to provide meteorological fields suitable for microscale boundary forcing. The model parameterization is described in Table 1.

Parameter	Nest (D3)	Parent (D2, D1)
Timestep	0.4s	2s, 10s
Resolution	160x120	91x86, 94x98
Grid size	110m	550m, 2800m
Vertical levels	100	100
Shortwave radiation	RRTMG	RRTMG
Longwave radiation	RRTMG	RRTMG
Microphysics	Kessler	Kessler
Cumulus	-	-, Kain-Fritsch
Boundary layer	YSU	YSU
Surface layer	MM5	MM5
Land-surface model	Unified NOAH LSM	Unified NOAH LSM
Urban model	UCM	UCM

Table 1. WRF model configuration.

Initial and boundary atmospheric conditions for the WRF simulations were obtained from the ERA5 global reanalysis dataset. The simulations produced temporally continuous fields of near-surface air temperature, wind speed, wind direction, humidity, and turbulence-related variables, which were subsequently used as forcing conditions for the microscale model. The use of WRF-UCM enabled the representation of urban heat island processes and surface–atmosphere interactions even under conditions of sparse observational coverage (Martilli et al., 2002; Salamanca et al., 2010).

The simulations covered a 24-hour period on 27 August 2023 during a heatwave event. A 24-hour spin-up period preceding the analysis was used for the WRF-UCM model, whereas a 19-hour spin-up period was applied to ENVI-met to ensure realistic initialization of microscale atmospheric processes.

High-resolution geospatial input data describing the urban environment were prepared using a combination of remote sensing and GIS datasets (Figure 2). Land cover information was derived from Sentinel-2 multispectral imagery and supplementary vector datasets representing roads, railways, and water bodies. Semi-automatic land cover classification was performed using the QGIS Semi-Automatic Classification Plugin (SCP), following procedures commonly applied in urban climate studies. The resulting land cover classes were generalized into categories compatible with the microscale modelling framework, including asphalt surfaces, bare soil, low vegetation, rail infrastructure, and water bodies.

Building morphology was derived from vector building footprints combined with LiDAR-based height estimation. Building heights were calculated from a canopy height model generated from airborne LiDAR point clouds, allowing preparation of Level of Detail 1 (LoD1) urban geometry suitable for microscale simulations. The resulting dataset represented the spatial distribution and average height of urban structures within the study domain.

Vegetation data were also extracted from LiDAR point clouds using automated tree detection approaches. Individual trees were represented as point features with attributes describing tree height and generalized vegetation type. The vegetation was categorized into several generalized classes based on canopy height and crown characteristics. This approach enabled realistic representation of urban greenery while maintaining computational efficiency. Full workflow of data preparation can be found in our publication Fedor et al. (2026).

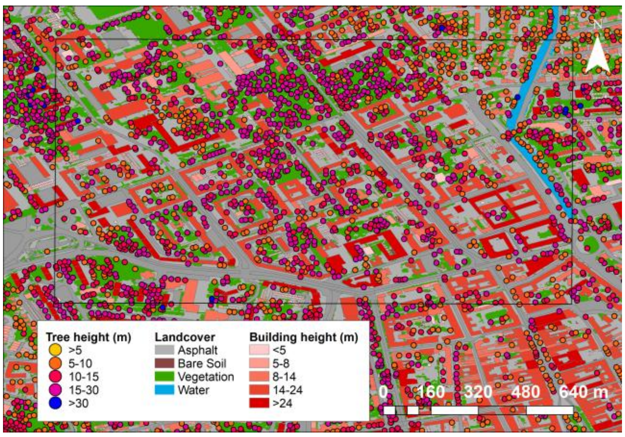

Figure 2. ENVI-met model domain with input geographical data.

The integration of WRF-UCM atmospheric outputs with detailed urban surface data created a consistent multi-scale modelling framework capable of simulating urban meteorological conditions in a data-scarce environment. The prepared datasets provided both physically consistent atmospheric forcing and realistic urban morphology necessary for high-resolution microscale simulations.

3. Methods

The presented modelling framework applies a multi-scale modelling approach that integrates mesoscale atmospheric simulations with high-resolution microscale urban climate modelling (Figure 3). The framework combines the Weather Research and Forecasting model coupled with an Urban Canopy Model (WRF-UCM) (Kusaka et al., 2004) and the ENVI-met microscale model (Bruse and Fleer, 1998), which has been widely applied and validated in urban microclimate studies (Tsoka et al., 2018). The workflow combines open-source atmospheric modelling, GIS processing, and remote sensing methods into a reproducible multi-scale urban climate modelling framework.

The modelling chain begins with large-scale atmospheric reanalysis data obtained from ERA5, which provide initial and boundary conditions for mesoscale numerical weather prediction simulations. These datasets contain temporally continuous atmospheric information describing regional circulation, temperature, humidity and wind fields necessary for realistic simulation of atmospheric processes.

The mesoscale component of the framework is represented by the WRF model parameterized with the Single-Layer Urban Canopy Model (SLUCM) (Kusaka et al., 2004). The WRF-UCM simulation was configured using nested computational domains with progressively finer spatial resolution in order to capture both regional atmospheric dynamics and local urban influences. Urban land cover classes and updated surface datasets were incorporated into the preprocessing stage to improve representation of built-up areas and surface-atmosphere interactions. The WRF-UCM model produced continuous atmospheric outputs, including near-surface temperature, humidity, wind speed, wind direction, and boundary layer characteristics relevant for urban climate analysis (Figure 4).

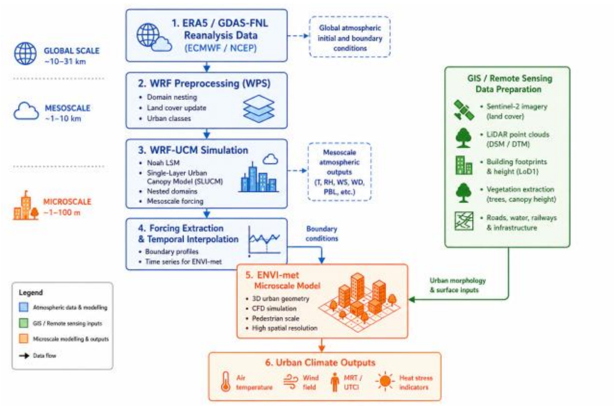

Figure 3. Multi-scale modelling workflow integrating mesoscale WRF-UCM simulations with ENVI-met microscale modelling. Atmospheric boundary conditions generated from ERA5-driven WRF-UCM simulations were extracted for use as forcing data in ENVI-met, while high-resolution urban morphology inputs were prepared from GIS and remote sensing datasets.

Outputs from the innermost WRF-UCM domain were subsequently processed to generate forcing data for the microscale simulations. This step included extraction of temporal atmospheric variables into formats compatible with ENVI-met input boundary conditions. The generated forcing data provided dynamically consistent atmospheric inputs for the microscale model while preserving the influence of regional and mesoscale weather conditions. The extracted WRF-UCM variables included air temperature, relative humidity, wind speed, and wind direction in 10-minute intervals. The variables were extracted from the WRF-UCM grid cell covering the ENVI-met domain.

In parallel, detailed urban morphology datasets were prepared using GIS and remote sensing methods. High-resolution land cover information was derived from Sentinel-2 multispectral imagery, while building geometry and vegetation structure were extracted from LiDAR point clouds and vector datasets. The prepared datasets included surface classes, building footprints and heights, vegetation distribution, and transportation infrastructure necessary for realistic representation of the urban canopy within the microscale model.

The ENVI-met model was then used to simulate microscale atmospheric processes within the selected urban domain. The model resolved airflow, turbulence, radiation exchange, and thermal interactions at pedestrian scale using detailed three-dimensional urban geometry. By coupling WRF-UCM atmospheric forcing with high-resolution urban surface data, the framework enabled downscaling of atmospheric conditions to the microscale level.

The proposed workflow demonstrates how open-source atmospheric models, GIS tools, and remote sensing datasets can be integrated into a reproducible multi-scale urban climate modelling framework. The methodology is particularly suitable for medium-sized cities and regions where dense meteorological observation networks are unavailable, allowing physically consistent microscale simulations driven by mesoscale atmospheric conditions.

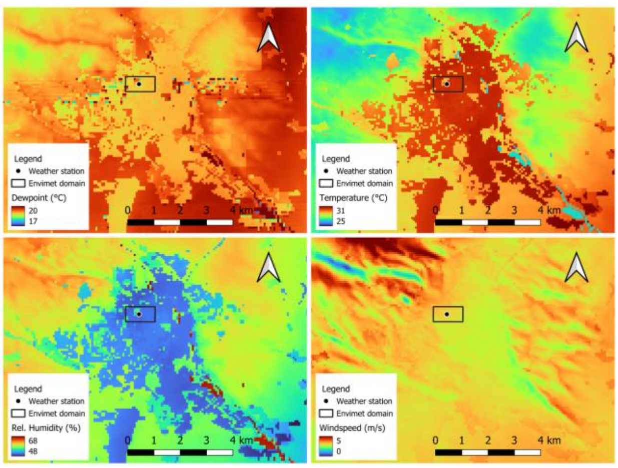

Figure 4. WRF-UCM output examples from D3 domain: 2 m dewpoint, temperature, relative humidity and 10 m windspeed at 14:00 UTC with marked weather station and ENVI-met model domain.

4. Results

4.1 ENVI-met simulation outputs

The WRF-UCM-derived forcing data were successfully applied as meteorological initial and boundary conditions for the ENVI-met simulations (Bruse and Fleer, 1998; Toparlar et al., 2017). The resulting microscale simulations reproduced spatial variability of key urban climate variables at neighbourhood scale.

Figure 5 presents selected ENVI-met outputs at pedestrian level. The simulated air temperature field reflects the influence of urban morphology and land cover heterogeneity, with higher temperatures occurring in densely built-up areas and on impervious surfaces. Cooler conditions were observed in vegetated areas and locations influenced by shading from buildings and trees. Relative humidity exhibited an inverse spatial pattern, with lower values in warmer urban locations and higher values in shaded and vegetated areas.

Wind speed distributions revealed strong microscale effects induced by building geometry. Enhanced airflow occurred along open corridors and streets aligned with the prevailing wind direction, while reduced wind speeds were observed within enclosed urban blocks and sheltered locations. These patterns cannot be resolved by mesoscale models alone and demonstrate the added value of microscale simulations driven by WRF-UCM boundary conditions.

The UTCI maps indicate considerable spatial variability of thermal stress within the study area, consistent with previous ENVI-met-based thermal comfort studies (Fedor et al., 2025; Fedor et al., 2026). Areas exposed to direct solar radiation and characterized by limited shading exhibited the highest UTCI values, whereas shaded streets and green spaces provided more favourable thermal comfort conditions. The results demonstrate the capability of the proposed modelling framework to identify local thermal stress hotspots relevant for urban planning and climate adaptation measures.

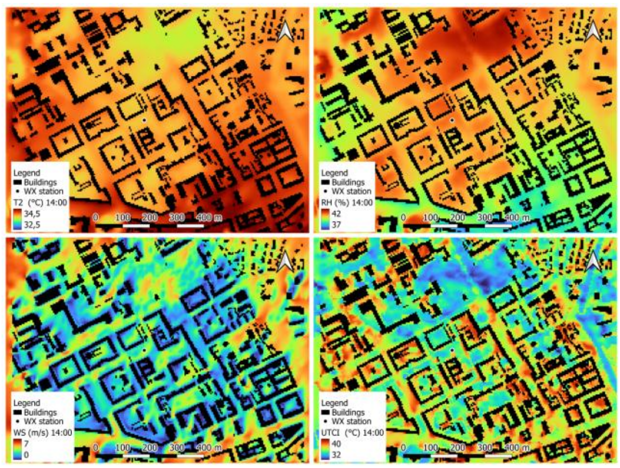

Figure 5. ENVI-met outputs: 2 meters temperature (T2), relative humidity (RH), wind speed (WS) and UTCI.

4.2 Comparison with observations

The performance of the coupled modelling framework was evaluated by comparing simulated meteorological variables with observations from a local weather station. Validation was performed using observations from an automatic weather station located within the ENVI-met domain (Figure 4 and Figure 5). Air temperature and relative humidity were evaluated at 2 m above ground level, while wind variables were compared at the nearest available model level (14 m above ground). Figures 6 and 7 show time series comparisons for air temperature (T2), relative humidity (RH), wind speed (WS), and wind direction (WD).

Both WRF-UCM and ENVI-met reproduced the general temporal evolution of observed meteorological conditions. However, ENVI-met simulations driven by WRF-UCM forcing showed a consistent improvement relative to the mesoscale outputs alone. For air temperature, the mean absolute error decreased from 2.13 °C for WRF-UCM to 1.95 °C for ENVI-met, while the Root Mean Square Error (RMSE) decreased from 2.69 °C to 2.44 °C. Similar improvements were observed for relative humidity, where Mean Absolute Error (MAE) decreased from 10.63 % to 9.91 % and RMSE from 13.32 % to 12.15 %.

The largest improvement was achieved for wind speed. ENVI-met reduced MAE from 1.91 m s^{-1} to 1.43 m s^{-1} and RMSE from 2.23 m s^{-1} to 1.69 m s^{-1}. This result reflects the ability of the microscale model to represent local aerodynamic effects associated with buildings and urban roughness (Toparlar et al., 2017). Wind direction remained comparable for both models because the parameter was evaluated at the top of the urban canopy layer, with mean wind direction difference (MWDD) values of approximately 81°.

The WRF model underestimated the radiative cooling during the day, which can be linked to generalisation of surface and its urban parameterisation and overestimation of the wind speed during the night (stronger mixing expected). This error was also transferred into microscale ENVI-met simulation. The WRF model, however, almost exactly depicted the mesoscale outflow boundary passing through the study area at 17:00 UTC on the first day of simulation, which helped to realistically depict the rapid change of meteorological variables.

Overall, the validation results indicate that WRF-UCM provides physically consistent boundary forcing for microscale simulations and that the coupled WRF-UCM/ENVI-met approach improves representation of near-surface meteorological conditions compared with mesoscale modelling alone. The results support the applicability of the proposed workflow for urban climate studies in cities where detailed meteorological observations are limited or unavailable.

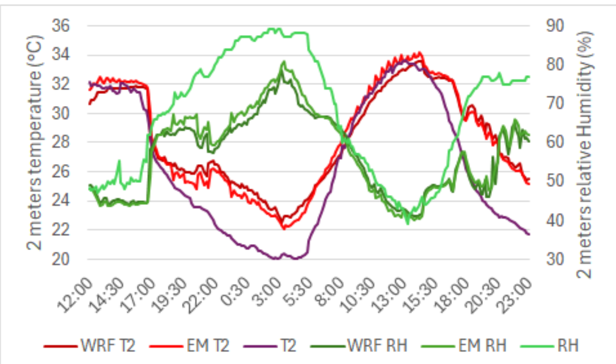

Figure 6. Comparison of 2 m temperature (T2) and relative humidity (RH) calculated by WRF-UCM (WRF) and ENVI-met (EM) with measured values.

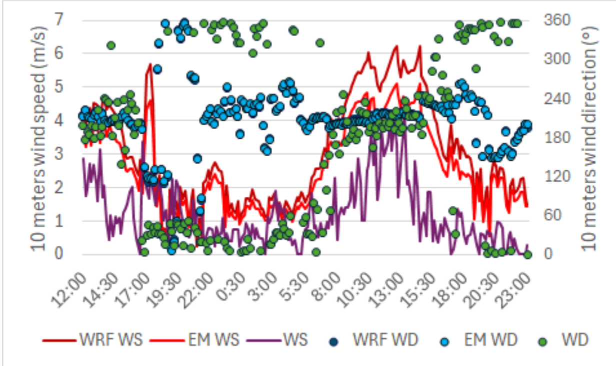

Figure 7. Comparison of 10 m wind speed (WS) and direction (WD) calculated by WRF-UCM (WRF) and ENVI-met (EM) with measured values.

	MAE	RMSE	MWDD
WRF T2	2.131	2.691	-
EM T2	1.952	2.438	-
WRF RH	10.631	13.315	-
EM RH	9.905	12.146	-
WRF WS	1.91	2.227	-
EM WS	1.431	1.686	-
WRF WD	-	-	81.481
EM WD	-	-	81.22

Table 2. Validation statistics of air temperature (T2), relative humidity, (RH) wind speed (WS) and direction (WD) derived from WRF-UCM (WRF) and ENVI-met (EM).

5. Discussion

The results demonstrate that WRF-UCM outputs can serve as a practical source of meteorological forcing for microscale urban climate simulations in environments where detailed observational datasets are unavailable and microscale model initialization and validation are lacking (Grimmond et al., 2010). This is particularly relevant for medium-sized cities such as Košice, where standard meteorological observations exist but dense urban monitoring networks required for microscale model initialization and validation are lacking.

The obtained temperature and wind errors (Table 2) are comparable to those reported in previous ENVI-met validation studies (Tsoka et al., 2018), indicating that the use of WRF-UCM forcing does not degrade the overall model performance. The comparison with observations also indicates that the coupled WRF-UCM/ENVI-met workflow is capable of reproducing the temporal variability of key meteorological variables with acceptable accuracy. While WRF-UCM captures the influence of regional atmospheric conditions and urban-scale processes (Chen et al., 2011; Salamanca et al., 2010), the ENVI-met simulations further improve the representation of near-surface conditions by explicitly resolving local interactions between airflow, buildings, vegetation, and surface materials.

ENVI-met reduced MAE by 8.4% for air temperature, 6.8% for relative humidity, and 25.1% for wind speed compared with WRF-UCM alone, demonstrating the added value of explicitly resolving local aerodynamic and thermal interactions at microscale. The results indicate that microscale airflow modifications induced by buildings and urban roughness play a significant role in determining pedestrian-level meteorological conditions and are only partially captured by parameterised mesoscale simulations.

The generated thermal comfort patterns further illustrate the benefits of the multi-scale approach. The simulations revealed substantial spatial variability in temperature, humidity, and UTCI within relatively small urban areas. Such variability is controlled primarily by local urban geometry, shading, vegetation, and surface characteristics (Oke et al., 2017; Fedor et al., 2026), which are represented in detail by ENVI-met but only indirectly within WRF-UCM. Consequently, the coupling approach enables analysis of urban heat stress at scales relevant for urban planning and climate adaptation measures while maintaining consistency with regional meteorological forcing.

An important advantage of the proposed workflow is the use of open and widely available datasets and modelling tools. ERA5 reanalysis data, WRF-UCM simulations, remote sensing products, and GIS-derived urban morphology datasets can be obtained for many cities worldwide. This makes the methodology transferable to regions where dedicated urban observation networks are unavailable and supports reproducible urban climate studies based on open-source geospatial technologies.

Several limitations should nevertheless be acknowledged. First, the coupling between WRF-UCM and ENVI-met was implemented as a one-way transfer of meteorological forcing (offline coupling). Feedback from microscale processes to the mesoscale atmosphere was therefore not represented. Second, the evaluation was based on a limited number of observation sites, restricting the assessment of spatial model performance. Additional measurements from urban meteorological networks would allow a more comprehensive evaluation of temperature, wind, and thermal comfort patterns. Third, uncertainties associated with urban morphology data, land-cover classification, and urban canopy parameterization may propagate through both modelling systems and influence the final results.

Future research should focus on testing the methodology under different synoptic situations, seasons, and urban configurations. Additional work could also investigate alternative urban canopy parameterizations within WRF, automated workflows for generating ENVI-met forcing data, and the use of emerging high-resolution geospatial datasets derived from LiDAR and Earth observation platforms. Such developments would further improve the applicability of multi-scale urban climate modelling in data-scarce environments.

Overall, the study demonstrates that WRF-UCM-derived forcing data provide a viable and physically consistent basis for microscale urban climate simulations. The proposed workflow bridges the gap between regional atmospheric modelling and local urban climate analysis, enabling detailed assessments of urban thermal conditions in cities where observational data are limited.

6. Conclusions

This study presented a multi-scale urban climate modelling framework that combines WRF-UCM mesoscale simulations with ENVI-met microscale modelling in order to generate physically consistent meteorological forcing for urban climate analyses in data-scarce environments. The workflow integrates open-source atmospheric modelling tools, remote sensing data, and GIS-based urban morphology datasets into a reproducible methodology applicable to medium-sized cities with limited meteorological observations.

The results demonstrate that WRF-UCM outputs can successfully provide boundary conditions for ENVI-met simulations while preserving the influence of regional atmospheric processes. The coupled modelling approach reproduced the temporal evolution of key meteorological variables and generated realistic spatial patterns of air temperature, humidity, wind conditions, and thermal comfort indicators within the urban environment. Comparison with observations showed that the microscale simulations driven by WRF-UCM forcing improved the representation of near-surface meteorological conditions relative to mesoscale modelling alone.

The proposed methodology offers a practical solution for urban climate studies in regions where dense observational networks are unavailable. By combining regional atmospheric forcing with detailed urban morphology, the framework enables high-resolution assessment of urban heat stress, ventilation conditions, and local microclimatic variability relevant for urban planning and climate adaptation.

Future work should focus on evaluating the approach under different meteorological situations, extending validation using multiple urban observation sites, and testing alternative urban canopy parameterizations. Further automation of the data processing workflow and integration with emerging Earth observation datasets could support wider adoption of multi-scale urban climate modelling within the open-source geospatial community.

The proposed workflow extends the applicability of ENVI-met to cities where detailed meteorological forcing data are unavailable, enabling high-resolution urban climate analyses based solely on regional atmospheric simulations and openly available geospatial datasets.

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