Technical Documentation of the WRFUP Package

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Abstract. This document provides a detailed technical overview of WRFUP, a Python package designed to automate the retrieval, processing, and ingestion of high-resolution urban morphology data into the Weather Research and Forecasting (WRF) model. WRFUP integrates datasets such as the World Settlement Footprint 3D (WSF3D) and Global Urban Fraction to compute urban canopy parameters, including urban fraction, plan area fraction (λ_P), total surface fraction (λ_B), mean building height, and frontal area index. The package is designed for compatibility with WRF's urban parameterizations (SLUCM, BEP, BEP+BEM) and ensures efficient data processing through automated tile selection, interpolation, and ingestion into WRF's `geo_em` file. The document describes the structure and workflow of WRFUP, including its modular architecture, data sources, and computational methodology. It also provides guidance on running WRFUP within the WRF preprocessing system and details the validation process, comparing WRFUP results against LiDAR data and the WUDAPT to WRF (`W2W`) approach. The results highlight the package's ability to produce high-accuracy urban morphology data with minimal user effort. Finally, the document outlines future development directions, including the integration of additional datasets and improvements in parameter estimation techniques.

1 Introduction

The WRFUP tool, is a Python package designed to enhance the accuracy of urban canopy parameterization in the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). By automating the ingestion of high-resolution urban morphology data, it ensures that WRF simulations accurately represent urban environments.

Urban canopy models such as SLUCM (Kusaka et al., 2001), BEP (Martilli et al., 2002), and BEP+BEM (Salamanca et al., 2010) in WRF require detailed urban morphology parameters, including building heights, urban fraction, and building fractions. Traditionally, these data are either unavailable or rely on LiDAR surveys which are complex to process and are not universally available.

One of the most widely used approaches for urban canopy parameterization in WRF is the World Urban Database and Access Portal Tool (WUDAPT) (Ching et al., 2018). WUDAPT provides a global classification of cities based on Local Climate Zones (LCZs) (Stewart & Oke, 2012), a framework that categorizes urban areas according to their built form and surface properties. This classification enables urban canopy models to assign representative values to urban morphology parameters such as urban fraction, building height, and roughness length.

Building upon WUDAPT, WUDAPT to WRF (`W2W`) (Demuzere et al., 2022) was developed to facilitate the integration of LCZ-based urban morphology into WRF. `W2W` extracts urban morphology parameters from predefined LCZ lookup tables, assigning values to WRF's urban canopy model based on the dominant LCZ in each grid cell. However, this approach relies on generalized table values rather than spatially explicit, high-resolution morphology data. While `W2W` provided an initial solution for urban parameterization, its reliance on LCZs limits its accuracy, particularly in cities with heterogeneous urban structures where local variations in building morphology are critical for urban climate modeling.

WRFUP (Gabeiras, 2024) advances this capability by leveraging state-of-the-art global datasets such as the World Settlement Footprint 3D (WSF3D) (Esch et al., 2022) and Global Urban Fraction (Patel & Roth, 2022). Furthermore, it introduces a novel dataset for Lambda_B (Total Surface Fraction), calculated in accordance with the Building Effect Parameterization (BEP) and Building Energy Model (BEM) methodologies. By combining these data sources and methodologies, WRFUP enables precise urban parameterization for high-resolution urban climate modeling.

This document describes the technical details of WRFUP, including its integration into the WRF preprocessing workflow, data sources, calculations, and comparisons with previous tools like `W2W`, as well as validation against LiDAR data.

1.1 Target Audience

This document is intended for:

- Researchers using WRF for urban climate simulations.
- Developers interested in modifying wrfup.
- Scientists seeking to understand urban morphology parameterization in WRF.

2 wrfup Integration in the WRF Preprocessing System (WPS)

The WRFUP package seamlessly integrates into the WRF Preprocessing System (WPS), enhancing the `geo_em` file with high-resolution urban morphology data. By doing so, it ensures compatibility with advanced urban parameterizations such as SLUCM, BEP, and BEP+BEM. Without WRFUP, the necessary fields (`FRC_URB2D` and `URB_PARAM`) may be missing or filled with default values, resulting in unrealistic urban climate simulations.

2.1 Role of wrfup in WPS

The standard WPS workflow consists of three main steps:

1. **`geogrid.exe`**: Generates the `geo_em.d0X.nc` file with land surface data.
2. **`metgrid.exe`**: Combines the `geo_em` file with meteorological input data.

3. **`real.exe` and `wrf.exe`**: Run the WRF simulation using the processed input files.

WRFUP is applied after `geogrid.exe` but before `metgrid.exe`. It modifies the `geo_em` file by:

- Adding or updating the `FRC_URB2D` and `URB_PARAM` fields.
- Ensuring consistency between urban fraction and urban morphology parameters.
- Updating the flags (`FRC_URB2D_flag` and `URB_PARAM_flag`) to indicate that the fields should be used in later stages of the WRF simulation.

The modified `geo_em` file is then passed to `metgrid.exe` for further processing with meteorological input.

2.2 Running wrfup

To apply WRFUP after `geogrid.exe`, the following command is used:

```
wrfup geo_em.d0X.nc URB_PARAM --work_dir YOUR_DIRECTORY
```

or

```
wrfup geo_em.d0X.nc FRC_URB2D --work_dir YOUR_DIRECTORY
```

After executing WRFUP, the modified file is typically renamed back to `geo_em.d0X.nc` before running `metgrid.exe`:

```
mv geo_em_URB_PARAM.nc geo_em.d0X.nc
```

3 Data Sources and Storage Structure

The accuracy of WRFUP relies on high-quality urban morphology datasets, carefully processed to ensure compatibility with the WRF model. This section describes the data sources, preprocessing methods, and the calculation of the total surface fraction (λ_B), a key parameter for urban canopy models.

3.1 Data Sources

WRFUP integrates two primary global datasets and generates a custom dataset for its calculations:

1. **Global Urban Fraction (100 m resolution) (Patel & Roth, 2022):** A dataset representing the fraction of urban land within each grid cell, used to isolate urban regions from non-urban areas in the model.
2. **World Settlement Footprint 3D (WSF3D) (Esch et al., 2022):** A 90 m-resolution global dataset providing:
   - **Plan Area Fraction (λ_P):** The fraction of land covered by buildings in a grid cell.
   - **Building Heights:** Average building heights, weighted by building footprint areas.
3. **Custom Lambda_B Dataset (Total Surface Fraction) (Gabeiras, 2025):** Lambda_B represents the total exposed surface fraction, including building walls and roofs, calculated using a methodology consistent with the BEP+BEM approach. It combines geometric relationships (building width, street width) with urban density metrics, ensuring accurate representation of urban areas.

3.2 Lambda_B Calculation

For the calculation of Lambda_B , the datasets described were supplemented with the global Local Climate Zone (LCZ) map from the WUDAPT project to incorporate height-to-width (H2W) ratio information, which was derived from the mid-point table of the Stewart and Oke LCZ classifications. Lambda_B is derived as:

$$\lambda_B = \lambda_P + \lambda_F \tag{1}$$

where:

- λ_P is the **plan area fraction** (horizontal surface coverage of buildings).
- λ_F is the **frontal area fraction** (vertical wall area of buildings exposed to the atmosphere).

λ_F is computed using:

$$\lambda_F = \frac{4 \cdot H \cdot BW \cdot UF}{(BW + SW)^2} \tag{2}$$

where:

- H is the **building height**.
- BW is the **building width**, given by:

$$BW = \frac{\lambda_P}{UrbanFraction - \lambda_P} \cdot SW \tag{3}$$

- SW is the **street width**, calculated as:

$$SW = \frac{MH}{H2W} \tag{4}$$

  where MH is the mean building height from WSF3D, and $H2W$ is the height-to-width ratio derived from the mid-point table of the Stewart and Oke LCZ classifications.

The physical interpretation is the following. This equation models buildings as simplified squares or rectangular prisms, assuming each building contributes four vertical walls (North, South, East, West). The Urban Fraction UF term ensures that only the urban portion of the grid is considered, consistent with how BEP+BEM operate. The part of the numerator $(4 \cdot H \cdot BW)$ represents the total wall surface area, while the denominator $((BW + SW)^2)$ normalizes this value to the total grid cell size, including streets and open spaces.

3.3 Preprocessing and Alignment

The datasets are preprocessed to ensure consistency and efficiency:

1. **Resampling:** All datasets are resampled to a 100 m resolution using bilinear interpolation for continuous variables. The projection of all datasets is set to WGS 84 (EPSG:4326), ensuring compatibility with global coordinate standards.
2. **Extent Matching:** Datasets are cropped to a common extent, spanning latitudes from $-60°$ to $84°$ and longitudes from $-180°$ to $180°$.
3. **Tiling:** The processed rasters are divided into a 16×16 grid, with each tile labeled by row and column indices (e.g., `00_00` for the top-left tile).

A visualization of this tiling system is provided in Figure 1, showing the dataset extent and tile indices:

3.4 Storage Structure

The tiles are stored in a github repository (Gabeiras, 2025) with efficiency and future compatibility in mind:

- **File Format:** Each tile is stored as `int8`, with scaling factors applied to preserve precision. For example, λ_P values are scaled by 100, and λ_B values by 20.
- **Compression:** Files are compressed using the ZIP format, significantly reducing storage requirements.
- **Content:**
  - **Urban Fraction tiles** contain a single band representing the urban fraction and is stored in the github repository: `data/01_BuildingFraction_WSF3D/zoom_4`.
  - **Urban Parameters tiles** stored in `data/01_URB_PARAM/zoom_4`, contain 3-band rasters:
    1. λ_P (Band 1)
    2. λ_B (Band 2)
    3. Building Height (Band 3)

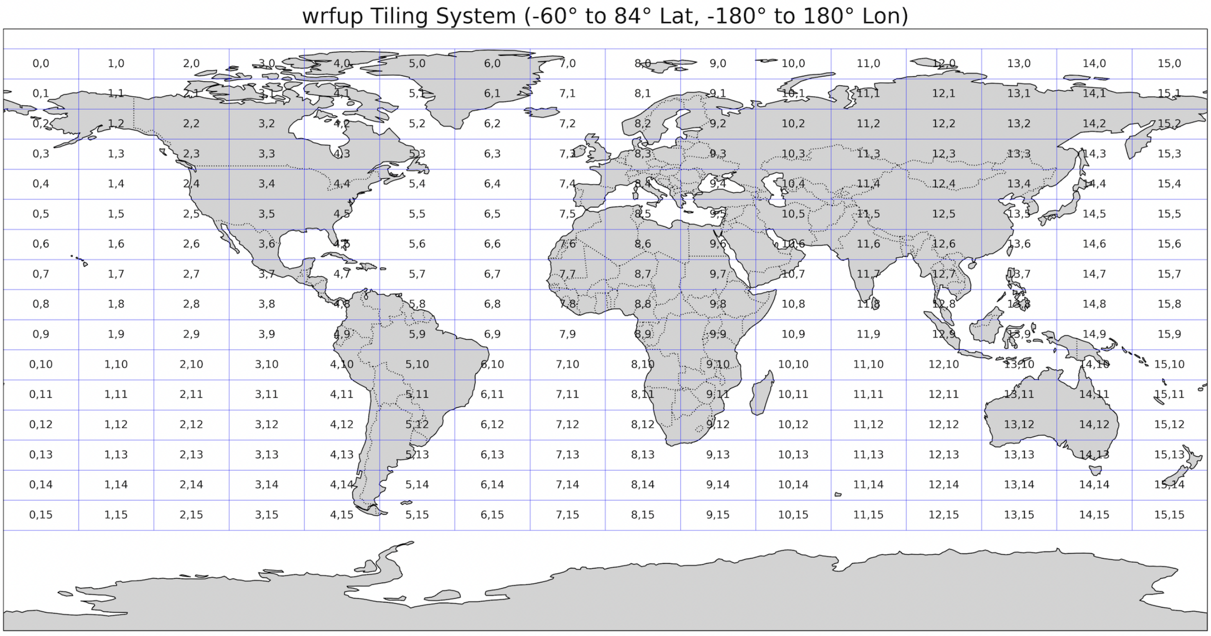

Figure 1: Tiling system for WRFUP datasets, with each tile indexed (row, column) and the top-left tile as (0,0).

3.5 Advantages

The system offers several benefits:

- **Scalability:** Designed to integrate with state-of-the-art datasets in the future. Substituting newer datasets for building height or urban fraction requires no changes to the methodology—only the input rasters.

- **Efficiency:** By tiling the data, WRFUP processes and retrieves only the tiles necessary for a specific region, minimizing computation and memory usage.
- **Compact Storage:** The use of scaling factors and compression ensures lightweight data without sacrificing accuracy.
- **Compatibility:** The approach aligns seamlessly with WRF's gridded framework, allowing for easy integration into simulations.

4 Calculations and Data Processing in wrfup

The WRFUP package extracts and processes urban morphology data from global datasets before integrating it into WRF's `geo_em` file. Since WRF operates on a user-defined domain resolution, WRFUP ensures that urban parameters are extracted, regridded, and ingested consistently.

4.1 1. Data Preparation Before Processing

Before performing any calculations, WRFUP follows these steps:

1. **Reads the `geo_em` file** to determine the simulation domain's spatial extent and resolution.
2. **Identifies the required tiles** from the global Urban Fraction and Urban Parameters datasets.
3. **Downloads** only the necessary tiles to optimize efficiency. The files are stored in a temporary directory called *temp*.
4. **Merges** the selected tiles to fully cover the WRF domain. The merged filed is saved in the temporary directory.

After merging the data, WRFUP ensures that the `FRC_URB2D` and `URB_PARAM` fields exist in the `geo_em` file:

- If `FRC_URB2D` or `URB_PARAM` are missing, they are **created**.
- If they exist, their **dimensions are checked** to ensure consistency with the WRF grid.
- `FRC_URB2D_flag` and `URB_PARAM_flag` are set to **1** in the `geo_em` file to ensure they are accounted for in later WRF processing steps.

Once these checks and preparations are complete, WRFUP proceeds with the calculations.

4.2 2. Handling Different Grid Resolutions

Since the input datasets are at **100 m resolution**, while WRF's urban grid may be finer or coarser, WRFUP applies the following regridding strategy:

- If the WRF grid resolution is **finer than 100 m**, values are **interpolated using bilinear interpolation**.
- If the WRF grid resolution is **coarser than 100 m**, values are **aggregated using an area-weighted mean**.

This ensures a smooth and consistent integration of urban parameters into WRF.

4.3 3. Urban Fraction (*UF*)

The Urban Fraction (*UF*) represents the proportion of a WRF grid cell classified as urban. Since WRF operates on a coarser grid than the raw data (100 m), WRFUP regrids *UF* to match WRF's domain resolution:

$$UF = \frac{\sum UF_{\text{raster}}}{N} \tag{5}$$

where:

- UF_{raster} is extracted from the Urban Fraction dataset.
- N is the number of 100 m raster cells contributing to a WRF grid cell.

If the WRF grid is finer than 100 m, *UF* is interpolated; otherwise, it is aggregated.

4.4 4. Plan Area Fraction (λ_P)

λ_P represents the fraction of the grid cell occupied by buildings. Since BEP and BEP+BEM require consistency between urban fraction and building fraction, λ_P is adjusted accordingly:

$$\lambda_P = \frac{\sum \lambda_P^{\text{URB}}}{N} \cdot UF \tag{6}$$

where:

- λ_P^{URB} is extracted from the Lambda_P band of the URB_PARAM dataset (originally from WSF3D).
- UF ensures consistency with BEP/BEM.
- N is the number of raster cells contributing to the WRF grid cell.

The processed λ_P values are interpolated if the WRF grid is finer than 100 m and aggregated if coarser.

4.5 5. Mean Building Height (H_{mean})

H_{mean} represents the average height of buildings in the WRF grid cell, weighted by λ_P:

$$H_{\text{mean}} = \frac{\sum (H^{\text{URB}} \cdot \lambda_P)}{\sum \lambda_P} \tag{7}$$

where:

- H^{URB} is extracted from the Building Height band of the URB_PARAM dataset (originally from WSF3D).
- λ_P ensures height consistency with building fraction.

Regridding follows the same rules as λ_P.

4.6 6. Total Surface Fraction (λ_B)

λ_B quantifies the total urban surface exposure, including both roofs and walls. It is computed similarly to λ_P, ensuring consistency with BEP/BEM:

$$\lambda_B = \frac{\sum \lambda_B^{\text{URB}}}{N} \cdot UF \tag{8}$$

where:

- λ_B^{URB} is extracted from the Lambda_B band of the URB_PARAM dataset.
- UF ensures consistency with urban fraction.

4.7 7. Frontal Area Index (FAI)

The Frontal Area Index (FAI) quantifies the wind-exposed vertical building surface area in four cardinal directions:

$$FAI_d = \frac{\sum (H^{\text{URB}} \cdot W)}{\sum A_{\text{cell}}} \tag{9}$$

where:

- H^{URB} is the mean building height.
- W is the facade width in direction d.

4.8 8. Building Height Distribution

To improve urban heterogeneity representation, WRFUP generates a height distribution for each WRF grid cell:

1. Heights are classified into 15 bins, from 0–5 m to 70+ meters.
2. Weighted by λ_P for consistency.
3. Aggregated to match the WRF grid resolution.

4.9 Summary of Processed Parameters and URB_PARAM Slices

Parameter	**Symbol**	**WRF Field**	**Slice**
Urban Fraction	UF	URB_FRC2D	-
Plan Area Fraction	λ_P	URB_PARAM	91
Mean Building Height	H_{mean}	URB_PARAM	92
Total Surface Fraction	λ_B	URB_PARAM	94
Frontal Area Index (N, S, E, W)	FAI	URB_PARAM	96:99
Building Height Distribution (15 bands)	-	URB_PARAM	117:132

Table 1: Summary of processed urban parameters, their corresponding WRF fields, and slice locations in the `geo_em` file.

5 wrfup Package Architecture

The WRFUP package follows a modular architecture, where each module is responsible for a specific part of the workflow. This design ensures efficiency, maintainability, and extensibility.

5.1 Modules and Responsibilities

The key modules in WRFUP and their responsibilities are as follows:

- **`download.py`: Data Acquisition**
  Handles the retrieval of urban morphology datasets for the specified area of interest (AOI). This module ensures that only the necessary tiles are downloaded, minimizing data transfer and storage.

- **`calculation.py`: Urban Parameter Computation**
  Computes essential urban canopy parameters (e.g., λ_P, H_{mean}, λ_B) using the downloaded data. These calculations ensure consistency with BEP/BEM methodologies.

- **`ingest.py`: Data Integration**
  Integrates the computed parameters into the WRF `geo_em` file. It ensures that fields such as `URB_PARAM` and `FRC_URB2D` are correctly updated or created if missing.

- **`utils.py`: Utilities and Helpers**
  Provides helper functions for file handling, data validation, and cleaning temporary files. It also checks the integrity of the `geo_em` file.

- **`main.py`: User Interface**
  Serves as the entry point for the package. This module provides a command-line interface, allowing users to execute tasks such as downloading data, performing calculations, and ingesting results.

5.2 Workflow and Module Interaction

The interaction between the modules follows a linear workflow:

1. **Data Acquisition** (`download.py`): Downloads the necessary datasets based on the AOI and merges tiles to align with the WRF domain.

2. **Urban Parameter Calculation** (`calculation.py`): Processes the merged datasets to compute required parameters.

3. **Data Integration** (`ingest.py`): Writes the computed parameters into the `geo_em` file, ensuring compatibility with WRF urban schemes.

4. **Utility Operations** (`utils.py`): Ensures file integrity, manages temporary files, and validates outputs.

5. **Execution and Interaction** (`main.py`): Enables users to trigger the workflow from the command line.

5.3 Extensibility and Scalability

The modular design of WRFUP allows for:

- **Easy Integration of New Data Sources:** Additional data sources can be incorporated by extending `download.py`.
- **Custom Parameter Calculations:** New urban canopy parameters can be added by modifying `calculation.py`.
- **Adaptation to Future WRF Updates:** Changes to WRF's `geo_em` file structure can be accommodated by updating `ingest.py`.

6 Validation

The validation of WRFUP was conducted through its application to the Grenoble metropolitan area and a comparison against two benchmarks: LiDAR data and the WUDAPT to WRF (`W2W`) tool. LiDAR data, with its high spatial resolution and precision, serves as the gold standard for urban morphology characterization. Meanwhile, `W2W` represents a prior state-of-the-art approach for integrating Local Climate Zone (LCZ)-based urban morphology into WRF, relying on generalized table values.

6.1 Application to Grenoble

The Grenoble metropolitan area serves as a representative example of the capabilities of WRFUP in transforming high-resolution urban morphology data into fields compatible with WRF's coarser domain resolution. Figure 2 illustrates the spatial distribution of urban fraction (UF), plan area fraction (λ_P), total surface fraction (λ_B), and mean building height (H_{mean}) ingested into a 200-meter WRF grid.

The maps highlight the ability of WRFUP to preserve the heterogeneity of urban environments. Dense urban regions, such as the city center, exhibit high values for λ_P, λ_B, and H_{mean}, while suburban and rural areas show lower values. This spatial fidelity ensures that critical urban features are accurately represented, enabling more realistic simulations of urban climate processes.

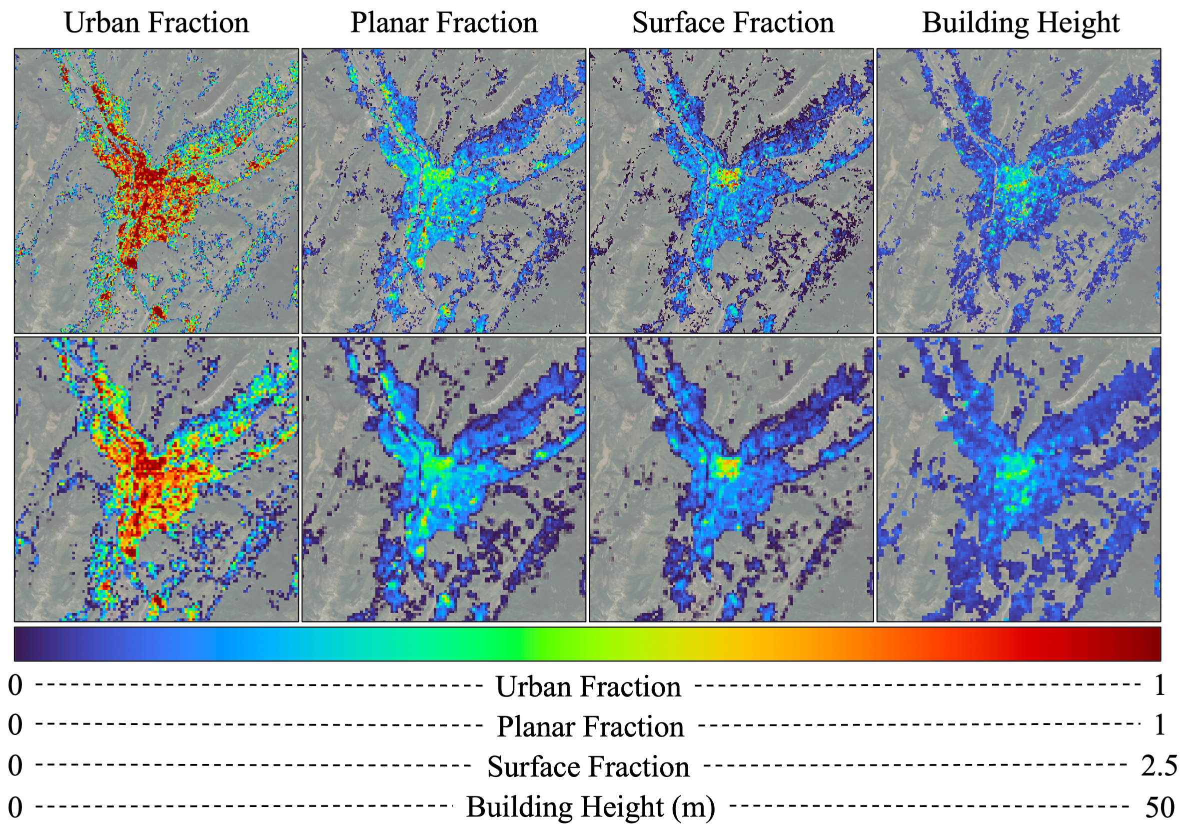

Figure 2: Integration of high-resolution urban morphology data into a 200-meter WRF grid for the Grenoble metropolitan area. The maps display urban fraction (UF), plan area fraction (λ_P), total surface fraction (λ_B), and mean building height (H_{mean}). The top row represents the sourced data in full resolution and the bottom row is the same data ingested into the model grid with the use of WRFUP.

6.2 Comparison with W2W and LiDAR Data

To assess the accuracy of WRFUP, its outputs were compared to both LiDAR data and the results from `W2W`. This comparison focused on key urban morphology parameters: UF, λ_P, λ_B, and H_{mean}. Figure 3 presents scatter plots and density distributions for these parameters, showing how WRFUP and `W2W` align with the benchmark LiDAR data.

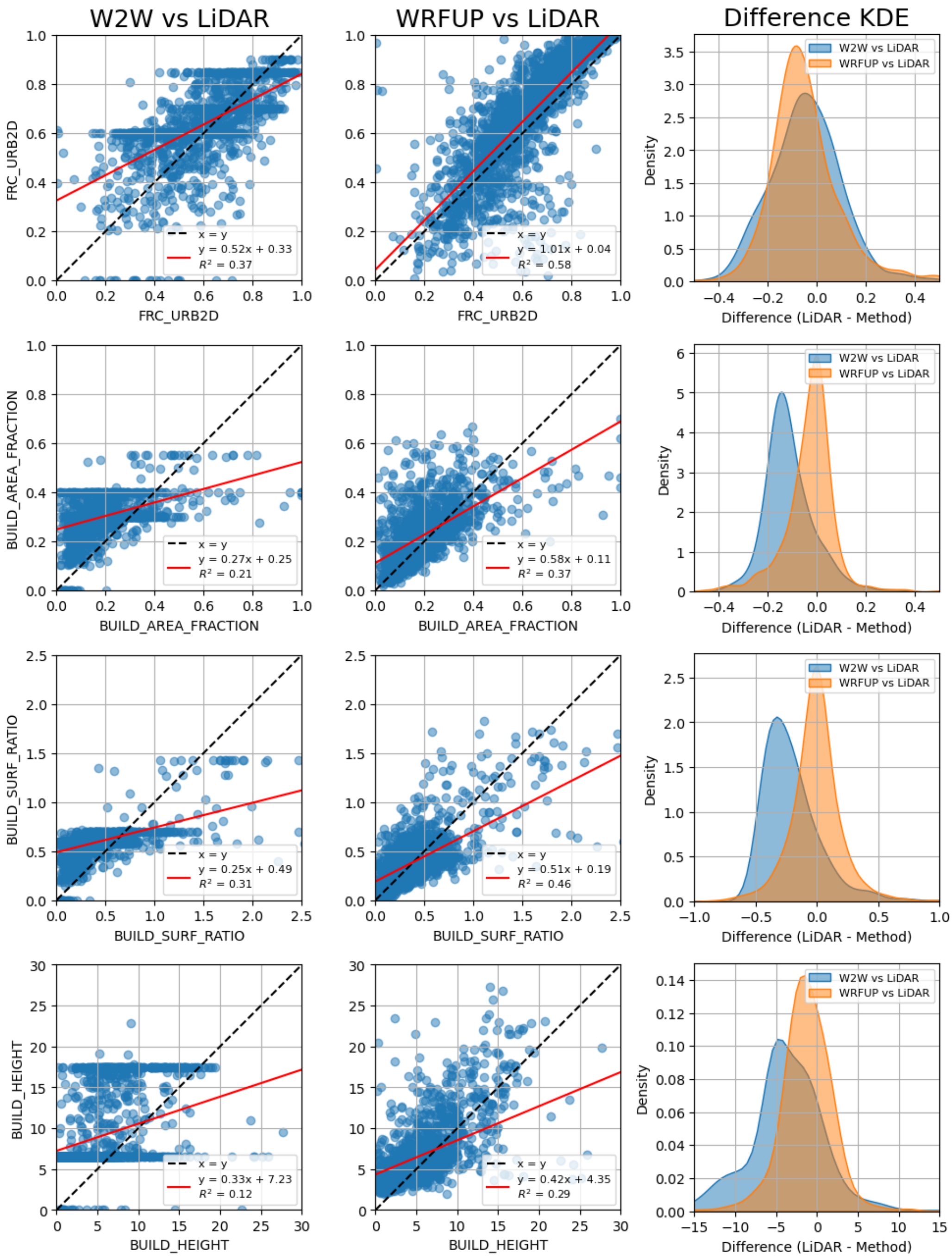

Figure 3: Validation results comparing WRFUP and `W2W` outputs against LiDAR data for key urban morphology parameters. Scatter plots illustrate correlations, while KDE plots show the distribution of differences.

The results demonstrate that WRFUP achieves a closer agreement with LiDAR-derived values compared to `W2W`. For all parameters, WRFUP exhibits reduced bias and higher correlation coefficients, particularly for complex metrics like λ_B and H_{mean}, which require consistency with BEP and BEM methodologies. In contrast, `W2W`, which relies on LCZ-based table values, shows greater discrepancies, particularly in areas with heterogeneous urban features.

The scatter plots in Figure 3 indicate that WRFUP not only reduces systematic bias but also provides better predictive performance for urban morphology parameters across different spatial scales. The KDE plots highlight narrower distributions of differences between WRFUP and LiDAR, demonstrating the robustness of WRFUP in replicating real-world urban characteristics.

6.3 Implications for Urban Climate Modeling

These results underscore the transformative potential of WRFUP for urban canopy parameterization in WRF. Previous approaches, such as `W2W`, relied on simplified LCZ-based parameterization, which, while innovative, was limited by its use of generalized values and inability to capture fine-scale urban heterogeneity. On the other hand, LiDAR data, while highly accurate, is often prohibitively expensive, computationally intensive, and geographically limited.

WRFUP bridges this gap by leveraging global, high-resolution datasets and integrating them with BEP/BEM-consistent methodologies. With just a single command, WRFUP processes and ingests urban morphology data that closely matches the accuracy of LiDAR-derived values. This combination of accessibility, efficiency, and accuracy positions WRFUP as a critical tool for urban climate modeling, enabling researchers to conduct high-fidelity simulations even in data-scarce regions.

7 Conclusions and Perspectives

7.1 Conclusions

The WRFUP package represents a significant step forward in urban canopy parameterization for the Weather Research and Forecasting (WRF) model. By leveraging global datasets such as WSF3D and Global Urban Fraction, and introducing the Lambda_B field with methodologies consistent with BEP and BEM schemes, WRFUP enables high-resolution urban morphology integration into WRF simulations.

Validation against LiDAR data demonstrates that WRFUP achieves accuracy comparable to this gold-standard urban morphology source while providing unprecedented scalability and efficiency. Unlike traditional methods such as `W2W`, which rely on generalized LCZ table values, WRFUP offers fine-scale spatial fidelity critical for urban climate modeling in heterogeneous urban environments. The ability to transform and ingest urban morphology data into WRF's framework with a single command makes WRFUP accessible and time-efficient, addressing the challenges of data availability and preprocessing in urban climate research.

This work positions WRFUP as a vital tool for urban climate studies, enabling researchers and city planners to model urban areas with high accuracy.

7.2 Perspectives

While WRFUP already provides robust functionality, several avenues for improvement and expansion remain:

- **Enhanced Lambda_B Calculation:** Future iterations of WRFUP could leverage machine learning techniques to improve the calculation of the Lambda_B field. By training models on high-resolution global datasets with LiDAR data post processed product as target, to derive Lambda_B more dynamically and accurately, accommodating complex urban morphologies that the current method approximates.

- **Integration of Emerging Datasets:** The inclusion of additional datasets, such as the recently developed GLOBUS project (Kamath et al., 2024), would allow WRFUP to expand its applicability. Datasets like GLOBUS provide global urban morphology data and could serve as valuable complements or alternatives to the current data sources.

- **Increased Flexibility in Urban Parameterization:** Incorporating the ability to handle user-defined urban parameters or additional fields could further enhance the tool's versatility for advanced users.

- **Improved Validation Metrics:** Expanding the validation framework to include additional cities with diverse urban morphologies and climates would help ensure the robustness of the package across various contexts. This could involve integrating datasets like satellite-derived urban morphology metrics or crowdsourced weather data for more comprehensive validation.

By continuing to refine its methodologies and incorporate emerging datasets and technologies, WRFUP has the potential to remain at the forefront of urban canopy modeling, facilitating high-resolution and efficient simulations that address the complexities of urban environments in a changing climate.

References

Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., Ren, C., Brousse, O., Martilli, A., Neophytou, M., Mouzourides, P., Stewart, I., Hanna, A., Ng, E., Foley, M., Alexander, P., Aliaga, D., Niyogi, D., Shreevastava, A., … Theeuwes, N. (2018). WUDAPT: An Urban Weather, Climate, and Environmental Modeling Infrastructure for the Anthropocene. *Bulletin of the American Meteorological Society*, *99*(9), 1907–1924. https://doi.org/10.1175/bams-d-16-0236.1

Demuzere, M., Argüeso, D., Zonato, A., & Kittner, J. (2022). W2W: A Python package that injects WUDAPT's Local Climate Zone information in WRF. *Journal of Open Source Software*, *7*(76), 4432. https://doi.org/10.21105/joss.04432

Esch, T., Brzoska, E., Dech, S., Leutner, B., Palacios-Lopez, D., Metz-Marconcini, A., Marconcini, M., Roth, A., & Zeidler, J. (2022). World Settlement Footprint 3D - A first three-dimensional survey of the global building stock. *Remote Sensing of Environment*, *270*, 112877. https://doi.org/10.1016/j.rse.2021.112877

Gabeiras, J. (2024). Wrfup: A Python package for urban parameter ingestion in WRF. https://github.com/jacobogabeiraspenas/wrfup
Accessed: 2024-05-15

Gabeiras, J. (2025). UrbanData01: High-resolution urban datasets for WRFUP package. https://github.com/jacobogabeiraspenas/UrbanData01
Accessed: 2025-02-06

Kamath, H. G., Singh, M., Malviya, N., Martilli, A., He, L., Aliaga, D., He, C., Chen, F., Magruder, L. A., Yang, Z.-L., & Niyogi, D. (2024). Global building heights for urban studies (ut-globus) for city- and street- scale urban simulations: Development and first applications. *Scientific Data*, *11*(1). https://doi.org/10.1038/s41597-024-03719-w

Kusaka, H., Kondo, H., Kikegawa, Y., & Kimura, F. (2001). A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Boundary-Layer Meteorology*, *101*(3), 329–358. https://doi.org/10.1023/a:1019207923078

Martilli, A., Clappier, A., & Rotach, M. W. (2002). An Urban Surface Exchange Parameterisation for Mesoscale Models. *Boundary-Layer Meteorology*, *104*(2), 261–304. https://doi.org/10.1023/A:1016099921195

Patel, P., & Roth, M. (2022). A High-Resolution Dataset of Global Urban Fraction for Mesoscale Urban Modelling. https://doi.org/10.5281/ZENODO.6994974

Salamanca, F., Krpo, A., Martilli, A., & Clappier, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—part I. formulation, verification, and sensitivity analysis of the model. *Theoretical and Applied Climatology*, *99*(3-4), 331–344. https://doi.org/10.1007/s00704-009-0142-9

Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Barker, D., Wang, W., Huang, X.-Y., & Duda, M. (2008). *A Description of the Advanced Research WRF Version 3* (tech. rep.). UCAR/NCAR. https://doi.org/10.5065/D68S4MVH

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. https://doi.org/10.1175/bams-d-11-00019.1