The Journal of Open Source Software

W2W: A Python package that injects WUDAPT's Local Climate Zone information in WRF

Matthias Demuzere [1¶], **Daniel Argüeso** [2], **Andrea Zonato** [3], and **Jonas Kittner** [1]

1 Urban Climatology Group, Department of Geography, Ruhr-University Bochum, Bochum, Germany **2** Physics Department, University of the Balearic Islands, Palma, Spain **3** Atmospheric Physics Group, Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy ¶ Corresponding author

DOI: 10.21105/joss.04432

Software

- Review
- Repository
- Archive

Editor: Chris Vernon

Reviewers:

- @thurber
- @erexer

Submitted: 22 April 2022
Published: 23 August 2022

Summary

The Python-based WUDAPT-to-WRF (`W2W`) package is developed to translate Local Climate Zone (LCZ) maps into urban canopy parameters readable by WRF, the community "Weather Research and Forecasting" model (Skamarock et al., 2021). It is the successor of the Fortran-based `W2W` package developed by Brousse et al. (2016) and Martilli et al. (2016), and provides an improved, simpler, and more efficient procedure to use LCZ information in WRF. Some important changes include direct manipulation of the geogrid files without the creation of temporary files, and the use of average LCZ-based urban morphological parameters instead of assigning them to the modal LCZ class.

This development of this package is in line with the objectives of WUDAPT, the World Urban Database and Access Portals Tools community project, that aims to 1) acquire and make accessible coherent and consistent information on the form and function of urban morphology relevant to climate weather and environmental studies, and 2) provide tools that extract relevant urban parameters and properties for models and model applications at appropriate scales for various climate, weather, environment, and urban planning purposes (Ching et al., 2018).

Statement of need

Since the pioneering work of Brousse et al. (2016) and Martilli et al. (2016), the level-0 WUDAPT information, the Local Climate Zone maps, have been used increasingly in WRF.

We expect this trend to continue because of three recent developments: 1) the creation of city-wide LCZ maps is now easier than ever with the launch of the LCZ Generator web application (Demuzere et al., 2021), 2) the availability of a global LCZ map (Demuzere et al., 2022), and 3) WRF versions $>$ 4.3 (Skamarock et al., 2021) can ingest 10 or 11 built classes (corresponding to WUDAPT's LCZs) by default, whereas previous WRF versions required manual code changes (see Martilli et al. (2016), Zonato & Chen (2021) and Zonato et al. (2021) for more information).

Because of these developments, an improved, Python-based, WUDAPT-to-WRF (`W2W`) routine is presented here to translate LCZ-based parameters better and simpler. It differs from its Fortran-based predecessor mainly by 1) using a more up-to-date LCZ-based urban extent, 2) aggregating the morphological parameters instead of using modal values, and 3) the fact that all processing is done with one (automated) tool, whereas the Fortran-based version required multiple pre-processing steps and manual namelist changes, described in more detail by Martilli et al. (2016).

Initial data requirements

To use the tool, two input files are required:

1. A **`geo_em.dXX`** (.nc) file for the inner WRF model domain in which one would like to use the LCZ-based information. This file can be produced by WRF's geogrid.exe tool as part of the WRF Preprocessing System (WPS), without additional modifications of the standard procedure.
2. A **Local Climate Zone map** (.tif) file that is slightly bigger than the domain extent of the `geo_em.dXX.nc` file. There are several ways to obtain an LCZ map for your region of interest (ROI):

- Extract your ROI from the global LCZ map (Demuzere et al., 2022), or the continental-scale LCZ maps for Europe (Demuzere et al., 2019) or the United States (Demuzere et al., 2020) (see here for more info).
- Check if your ROI is already covered by the many LCZ maps available in the submission table of the LCZ Generator.
- Use the LCZ Generator to make your LCZ map for your ROI. See here for more information. When using LCZ maps produced with the LCZ Generator, by default the Gaussian filtered LCZ map is used (corresponding to argument `--lcz-band = 1`).

Note: When using LCZ information from any of the large-scale LCZ maps, please make sure to crop your domain of interest first to avoid memory issues.

Workflow

The goal of the Python-based `W2W` tool is to obtain an inner WRF domain file (`geo_em.dXX.nc`) that contains the built LCZ classes and their corresponding urban canopy parameters relevant for all urban parameterizations embedded in WRF: the single-layer urban canopy model (Noah/SLUCM, Kusaka et al. (2001)), the Building Environment Parameterization (BEP, Martilli et al. (2002)), and BEP+BEM (Building Energy Model, Salamanca et al. (2010)).

To get to that point, a number of sequential steps are required:

Step 1: Remove the default urban land cover

The default urban land cover from MODIS is replaced with the dominant surrounding vegetation category, as done in Li et al. (2020). This procedure affects WRF's parameters LU_INDEX, LANDUSEF, and GREENFRAC. First, an initial number of neighboring pixels (corresponding argument `--npix-area`, default = `--npix-nlc` ** 2) are selected using scipy's k-d tree algorithm (Maneewongvatana & Mount, 1999), assuming a spherical Earth, and using the Euclidean distance along the great circle arc (i.e., section of the Earth that divides the sphere into two equal parts) to find the nearest pixels. Afterwards, the LU_INDEX is set by sampling the dominant category from the corresponding argument `--npix-nlc` (default = 45) nearest initial grid points (excluding ocean, urban, and lakes). GREENFRAC is calculated as the mean over all grid points with that dominant vegetation category among the `--npix-nlc` nearest points. For each grid point, if LANDUSEF had any percentage of urban, it is set to zero and the percentage is added to the dominant vegetation category assigned to that grid point.

Resulting output: **`geo_em.dXX_NoUrban.nc`**

Step 2: Define the LCZ-based urban extent

LCZ-based impervious fraction values (FRC_URB2D, available from `LCZ_UCP_default.csv`) are assigned to the original 100 m resolution LCZ map, and are aggregated to the WRF resolution. Areas with FRC_URB2D < 0.2 (corresponding to argument `--frc-threshold`) are currently considered non-urban. This choice has been made to avoid the use of the urban schemes in areas where the majority of the land use is vegetated since the impact of the impervious surfaces is low. The FRC_URB2D field is also used to mask all other urban parameter fields so that their extent is consistent.

Resulting output: **`geo_em.dXX_LCZ_extent.nc`**

Step 3: Introduce modal built LCZ classes

For each WRF grid cell, the mode of the underlying built LCZ classes is added to LU_INDEX (numbered from 31-41). See here for more info. Note that the `W2W` routine by default considers LCZ classes 1-10 as built classes (corresponding to argument `--built-lcz`). In some cases, also LCZ E (or 15 - Bare rock or paved) can be considered as a built LCZ class, as it might reflect large asphalt surfaces such as big parking lots or airstrips. In that case, the user must make sure the `--built-lcz` argument is set appropriately.

Step 4: Assign urban canopy parameters

Two procedures are followed when assigning the various urban canopy parameters to the LCZ map and translating this information onto WRF's grid:

Procedure 1: **Morphological parameters** are assigned directly to the high-resolution LCZ map, and are afterward aggregated to the lower-resolution WRF grid. As a result, the method produces a unique urban morphology parameter value for each WRF grid cell. This was found to be more efficient in reproducing urban boundary layer features, especially in the outskirts of the city (Zonato et al., 2020), and is in line with the WUDAPT-to-COSMO routine (Varentsov et al., 2020).

Morphological urban canopy parameter values are provided in `LCZ_UCP_default.csv` and are generally based on values provided in Stewart & Oke (2012) and Stewart et al. (2014). Note however that the values of MH_URB2D_MIN, MH_URB2D, and MH_URB2D_MAX for LCZ 7 are set to 4, 5, and 6 m instead of 2, 3, and 4 m because the minimum building height that can be assigned to BEP-BEM is 5m if dz_u = 5m (standard value) is used.

In addition:

- While `URBPARM_LCZ.TBL` (stored in WRF's `run/` folder) has values on street width (SW), `W2W` derives street width from the mean building height (MH_URB2D) and the Height-to-Width ratio (H2W), to have these fields consistent.
- Building width (BW), is derived from (BLDFR_URB2D/ (FRC_URB2D-BLDFR_URB2D)) * SW, these values are available in the look-up table `LCZ_UCP_default.csv`.
- Plan (LP_URB2D), frontal (LF_URB2D), and total (LB_URB2D) area indices are based on formulas in Zonato et al. (2020).
- HI_URB2D is obtained by fitting a bounded normal distribution to the minimum (MH_URB2D_MIN), mean (MH_URB2D), and maximum (MH_URB2D_MAX) building height, as provided in `LCZ_UCP_default.csv`. The building height standard deviation is also required and is approximated as (MH_URB2D_MAX - MH_URB2D_MIN) / 4.
- For computational efficiency, HI_URB2D values lower than 5% were set to 0 after resampling, and the remaining HI_URB2D percentages are re-scaled to 100%.

Procedure 2: In line with the former Fortran-based `W2W` procedure, **radiative and thermal parameters** are assigned to the modal LCZ class that is assigned to each WRF grid cell (see

Step 3). These parameter values are not stored in the NetCDF output but are read from URBPARM_LCZ.TBL and assigned automatically to the modal LCZ class when running the model.

Step 5: Adjust global attributes

In a final step, some global attributes are adjusted in the resulting NetCDF files:

- NBUI_MAX is added as a global attribute, reflecting the maximum amount of HI_URB2D classes that are not 0 across the model domain. This parameter can be used when compiling WRF to optimize memory storage.
- NUM_LAND_CAT is set to 41, to reflect the addition of 10 or 11 built LCZ classes. This is not only done for the highest resolution domain file (e.g. d04), but also for **all of its lower-resolution parent domain files (e.g. d01, d02, d03)**. As such, make sure these files are also available in the input data directory. In case the parent domain files have NUM_CAT_LAND $\neq$ 41, new parent domain files will be written to your drive with the extension _41.

Resulting output: **geo_em.dXX_LCZ_params.nc** (and **geo_em.dXX_41.nc**)

Integration in WRF's preprocessing

The current tool is designed to work with the geo_em.dXX files produced by geogrid.exe, which is available in the WRF Preprocessing System (WPS). WPS needs to be at a version >3.8, to incorporate the urban geometrical parameters in the URB_PARAM matrix (Glotfelty et al., 2013). The user should run geogrid.exe using its default settings, which will provide the various geo_em.dXX.nc files containing the static data fields. No additional variables are required, neither in the namelist.wps nor within the GEOGRID.TBL table. The W2W tool (Figure 1) reads the standard geo_em.dXX.nc files (for all the domains) and produces the aforementioned **geo_em.dXX_LCZ_params.nc** files. The user should then rename these files to the standard name for each of the domains (e.g. rename geo_em.d01_41.nc to geo_em.d01.nc and geo_em.d04_LCZ_params.nc to geo_em.d04.nc), which will serve as input to the metgrid.exe module (Figure 1).

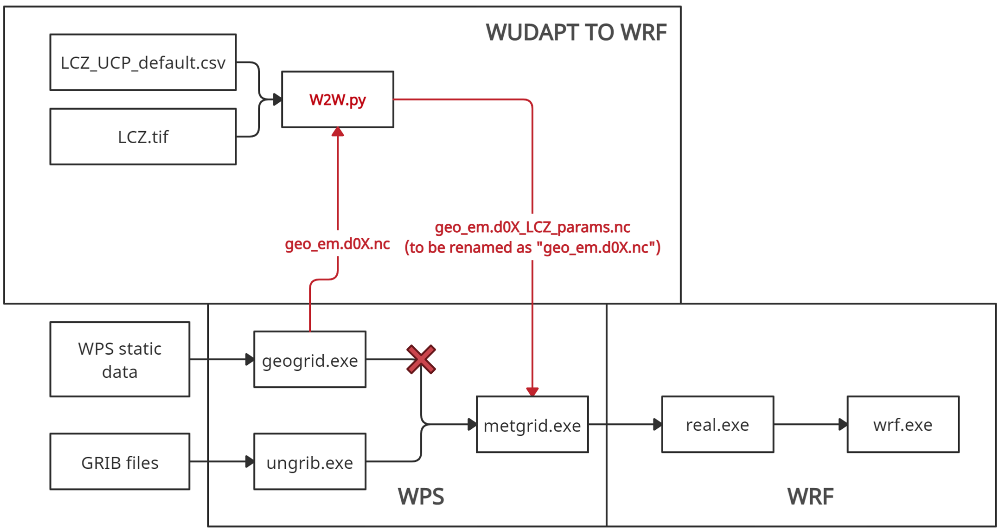

Figure 1: Modified workflow to set up and run a WRF simulation including urban parameters derived from LCZs using W2W.

Potential use cases

The files provided as output by W2W allow a wide range of applications, including - but not limited to - addressing the impact of:

- urbanization, by running WRF with the default geo_em.dXX.nc and the geo_em.dXX_NoUrban.nc files (see for example Li et al. (2020) and Hirsch et al. (2021)).
- an improved urban land cover extent description, by running WRF with the default geo_em.dXX.nc and the geo_em.dXX_LCZ_extent.nc files (similar to for example Bhati & Mohan (2018) and Mallard et al. (2018)).
- a more detailed (LCZ-based) urban description, by running WRF with the default geo_em.dXX.nc and the geo_em.dXX_LCZ_params.nc files (see for example Brousse et al. (2016), Hammerberg et al. (2018), Molnár et al. (2019), Wong et al. (2019), Patel et al. (2020), Zonato et al. (2020), Ribeiro et al. (2021), Hirsch et al. (2021) and Patel et al. (2022)).

Important notes

- Make sure to set use_wudapt_lcz=1 (default is 0) and num_land_cat=41 (default is 21) in WRF's namelist.input when using the LCZ-based urban canopy parameters.
- The LCZ-based urban canopy parameter values provided in LCZ_UCP_default.csv and URBPARM_LCZ.TBL are universal and generic, and might not be appropriate for your ROI. If available, please adjust the urban canopy parameters values according to the characteristics of your ROI. A custom csv file can be specified using the --lcz-ucp path/to/custom_file.csv flag.
- It is advised to use this tool with urban parameterization options BEP or BEP+BEM (sf_urban_physics = 2 or 3, respectively). In case you use this tool with the SLUCM model (sf_urban_physics = 1), make sure your lowest model level is above the highest building height. If not, real.exe will provide the following error message: ZDC + Z0C + 2m is larger than the 1st WRF level - Stop in subroutine urban - change ZDC and Z0C.
- At the end of running W2W, a note is displayed that indicates the nbui_max value, e.g. for the sample data: Set nbui_max to 5 during compilation, to optimize memory storage. This is especially relevant for users that work with the BEP or BEP+BEM urban parameterization schemes (sf_urban_physics = 2 or 3, respectively). See num_urban_nbui in WRF's README.namelist for more info.
- It is advised to use WRF versions > 4.3, that can ingest 10 or 11 built classes (corresponding to WUDAPT's LCZs) by default (Skamarock et al., 2021), and WPS versions > 3.8, to incorporate the urban geometrical parameters in the URB_PARAM matrix (Glotfelty et al., 2013).

Acknowledgements

We acknowledge contributions and support from Alberto Martilli, Alejandro Rodriguez Sanchez, and Oscar Brousse.

References

Bhati, S., & Mohan, M. (2018). WRF-urban canopy model evaluation for the assessment of heat island and thermal comfort over an urban airshed in India under varying land use/land cover conditions. *Geoscience Letters*, *5*(1). https://doi.org/10.1186/s40562-018-0126-7

Brousse, O., Martilli, A., Foley, M., Mills, G., & Bechtel, B. (2016). WUDAPT, an efficient land use producing data tool for mesoscale models? Integration of urban LCZ in WRF over madrid. *Urban Climate*, *17*, 116–134. https://doi.org/10.1016/j.uclim.2016.04.001

Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., Ren, C., Brorousse, O., Martilli, A., Neophytou, M., Mouzourides, P., Stewart, I., Hanna, A., Ng, E., Foley, M., Alexander, P., Aliaga, D., Niyogi, D., Shreevastava, A., … Theeuwesits, 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., Bechtel, B., Middel, A., & Mills, G. (2019). Mapping Europe into local climate zones. *PLOS ONE*, *14*(4), e0214474. https://doi.org/10.1371/journal.pone.0214474

Demuzere, M., Hankey, S., Mills, G., Zhang, W., Lu, T., & Bechtel, B. (2020). Combining expert and crowd-sourced training data to map urban form and functions for the continental US. *Scientific Data*, *7*(1), 264. https://doi.org/10.1038/s41597-020-00605-z

Demuzere, M., Kittner, J., & Bechtel, B. (2021). LCZ Generator: A Web Application to Create Local Climate Zone Maps. *Frontiers in Environmental Science*, *9*(April). https://doi.org/10.3389/fenvs.2021.637455

Demuzere, M., Kittner, J., Martilli, A., Mills, G., Moede, C., Stewart, I. D., Vliet, J. van, & Bechtel, B. (2022). A global map of Local Climate Zones to support earth system modelling and urban scale environmental science. *Earth System Science Data Discussions*. https://doi.org/10.5194/essd-2022-92

Glotfelty, T., Tewari, M., Sampson, K., Duda, M., Chen, F., & Ching, J. (2013). *NUDAPT 44: How to use NUDAPT dataset in WRF/SLUCM/MLUCM models* (p. 9). National Center for Atmospheric Research. https://www.yumpu.com/en/document/read/26871494/how-to-use-nudapt-dataset-in-wrf-slucm-mlucm-models

Hammerberg, K., Brousse, O., Martilli, A., & Mahdavi, A. (2018). Implications of employing detailed urban canopy parameters for mesoscale climate modelling: a comparison between WUDAPT and GIS databases over Vienna, Austria. *International Journal of Climatology*, *38*, e1241–e1257. https://doi.org/10.1002/joc.5447

Hirsch, A. L., Evans, J. P., Thomas, C., Conroy, B., Hart, M. A., Lipson, M., & Ertler, W. (2021). Resolving the influence of local flows on urban heat amplification during heatwaves. *Environmental Research Letters*, *16*(6), 064066. https://doi.org/10.1088/1748-9326/ac0377

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

Li, Y., Fowler, H. J., Argüeso, D., Blenkinsop, S., Evans, J. P., Lenderink, G., Yan, X., Guerreiro, S. B., Lewis, E., & Li, X. F. (2020). Strong Intensification of Hourly Rainfall Extremes by Urbanization. *Geophysical Research Letters*, *47*(14), 1–8. https://doi.org/10.1029/2020GL088758

Mallard, M. S., Spero, T. L., & Taylor, S. M. (2018). Examining WRF's sensitivity to contemporary land-use datasets across the contiguous united states using dynamical downscaling. *Journal of Applied Meteorology and Climatology*, *57*(11), 2561–2583. https://doi.org/10.1175/JAMC-D-17-0328.1

Maneewongvatana, S., & Mount, D. M. (1999). Analysis of Approximate Nearest Neighbor Searching with Clustered Point Sets. *Computer Science - ArXiv*. https://doi.org/10.48550/arXiv.cs/9901013

Martilli, A., Brousse, O., & Ching, J. (2016). *Urbanized WRF modeling using WUDAPT*. http://www.wudapt.org/wudapt-to-wrf/. https://www.wudapt.org/wp-content/uploads/2016/05/Urbanized-WRF-modeling-using-WUDAPT-web-version-March2016.pdf

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

Molnár, G., Gyöngyösi, A. Z., & Gál, T. (2019). Integration of an LCZ-based classification into WRF to assess the intra-urban temperature pattern under a heatwave period in Szeged, Hungary. *Theoretical and Applied Climatology*, *138*(1-2), 1139–1158. https://doi.org/10.1007/s00704-019-02881-1

Patel, P., Jamshidi, S., Nadimpalli, R., Aliaga, D. G., Mills, G., Chen, F., Demuzere, M., & Niyogi, D. (2022). Modelling Large-Scale Heatwave by Incorporating Enhanced Urban Representation. *Journal of Geophysical Research : Atmospheres*, *127*, 1–33. https://doi.org/10.1029/2021JD035316

Patel, P., Karmakar, S., Ghosh, S., & Niyogi, D. (2020). Improved simulation of very heavy rainfall events by incorporating WUDAPT urban land use/land cover in WRF. *Urban Climate*, *32*(July 2019), 100616. https://doi.org/10.1016/j.uclim.2020.100616

Ribeiro, I., Martilli, A., Falls, M., Zonato, A., & Villalba, G. (2021). Highly resolved WRF-BEP/BEM simulations over Barcelona urban area with LCZ. *Atmospheric Research*, *248*(August 2020), 105220. https://doi.org/10.1016/j.atmosres.2020.105220

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. C., Klemp, J. B., Dudhia, J. B., Gill, D. O., Liu, Z., Berner, J., Wang, W., Powers, J. G., Duda, M. G., Barker, D. M., & Huang, X.-Y. (2021). *A Description of the Advanced Research WRF Model Version 4.3* (July). National Center for Atmospheric Research. https://doi.org/10.5065/1dfh-6p97

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

Stewart, I. D., Oke, T. R., & Krayenhoff, E. S. (2014). Evaluation of the "local climate zone" scheme using temperature observations and model simulations [Journal Article]. *International Journal of Climatology*, *34*(4), 1062–1080. https://doi.org/10.1002/joc.3746

Varentsov, M., Samsonov, T., & Demuzere, M. (2020). Impact of Urban Canopy Parameters on a Megacity's Modelled Thermal Environment. *Atmosphere*, *11*(12), 1349. https://doi.org/10.3390/atmos11121349

Wong, M. M. F., Fung, J. C. H., Ching, J., Yeung, P. P. S., Tse, J. W. P., Ren, C., Wang, R., & Cai, M. (2019). Evaluation of uWRF performance and modeling guidance based on WUDAPT and NUDAPT UCP datasets for Hong Kong. *Urban Climate*, *28*(June 2018), 100460. https://doi.org/10.1016/j.uclim.2019.100460

Zonato, A., & Chen, F. (2021). *Updates of WRF-urban in WRF 4.3: Local Climate Zones, Mitigation Strategies, building materials permeability and new buildings drag coefficient*. http://www.wudapt.org/wudapt-to-wrf/. https://ral.ucar.edu/sites/default/files/public/product-tool/urban-canopy-model/WRF_urban_update_Readme_file_WRF4.3.pdf

Zonato, A., Martilli, A., Di Sabatino, S., Zardi, D., & Giovannini, L. (2020). Evaluating the performance of a novel WUDAPT averaging technique to define urban morphology with mesoscale models. *Urban Climate*, *31*(May 2019), 100584. https://doi.org/10.1016/j.uclim.2020.100584

Zonato, A., Martilli, A., Gutierrez, E., Chen, F., He, C., Barlage, M., Zardi, D., & Giovannini, L. (2021). Exploring the effects of rooftop mitigation strategies on urban temperatures and energy consumption. *Journal of Geophysical Research: Atmospheres*, 1–30. https://doi.org/10.1029/2021JD035002