Advancing CLMU for regional urban climate simulations through WRF coupling: intercomparison with NOAH–SLUCM

Yuan Sun[1], Keith W. Oleson[2], Cenlin He[2], Zhonghua Zheng[1]

[1] The University of Manchester
[2] NSF National Center for Atmospheric Research

CTSM/CLMU capability: scale dependency

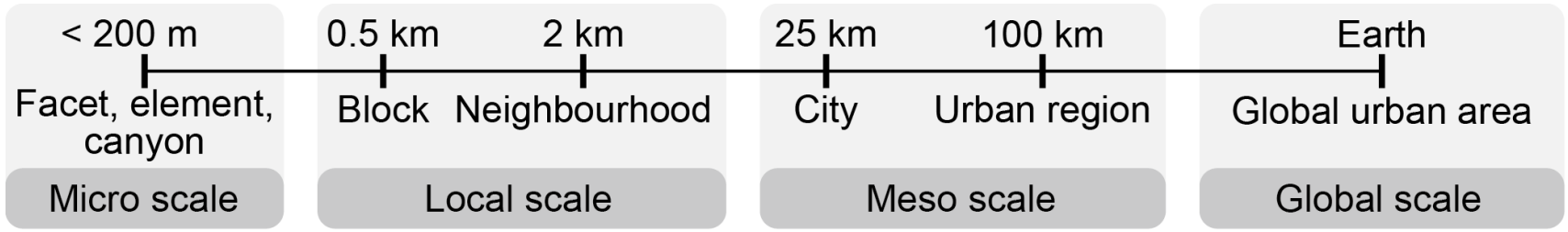
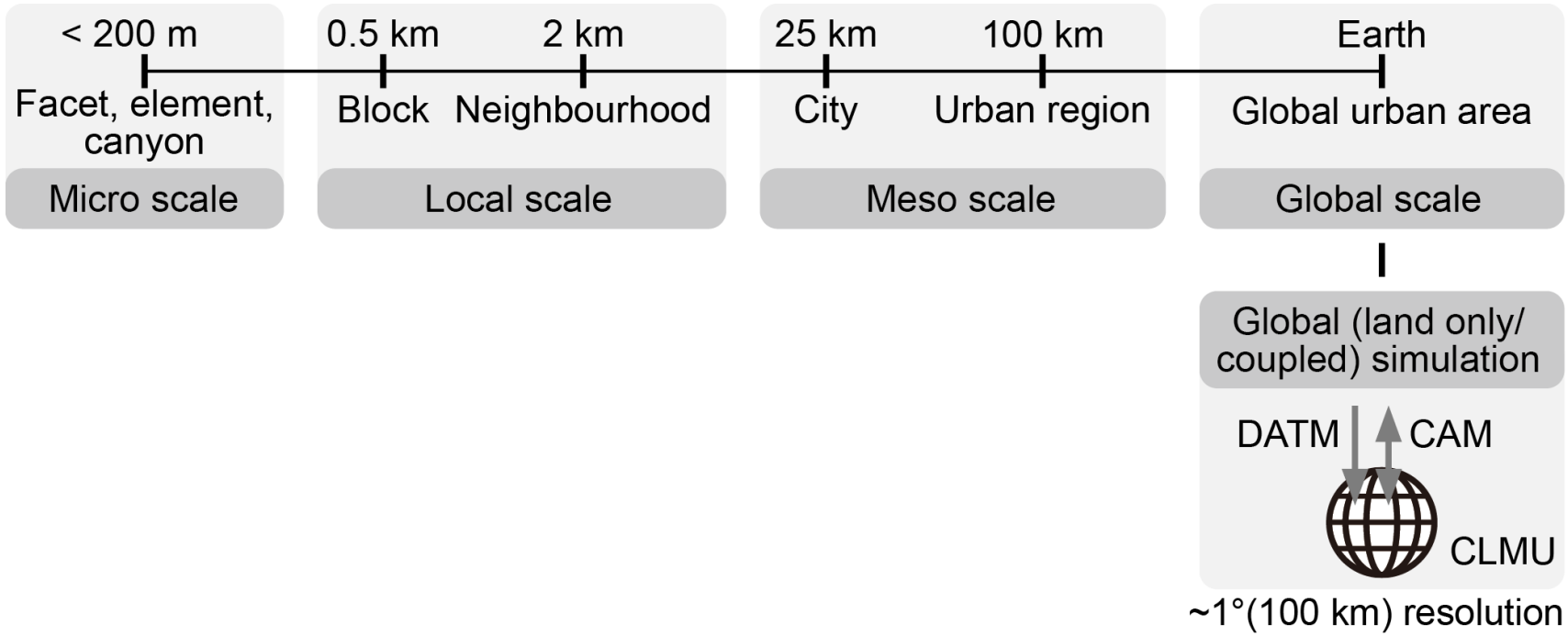


Fig. Capability of the CLMU in multi-scale urban climate modeling.

CTSM/CLMU capability: global



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CTSM/CLMU capability: single-point

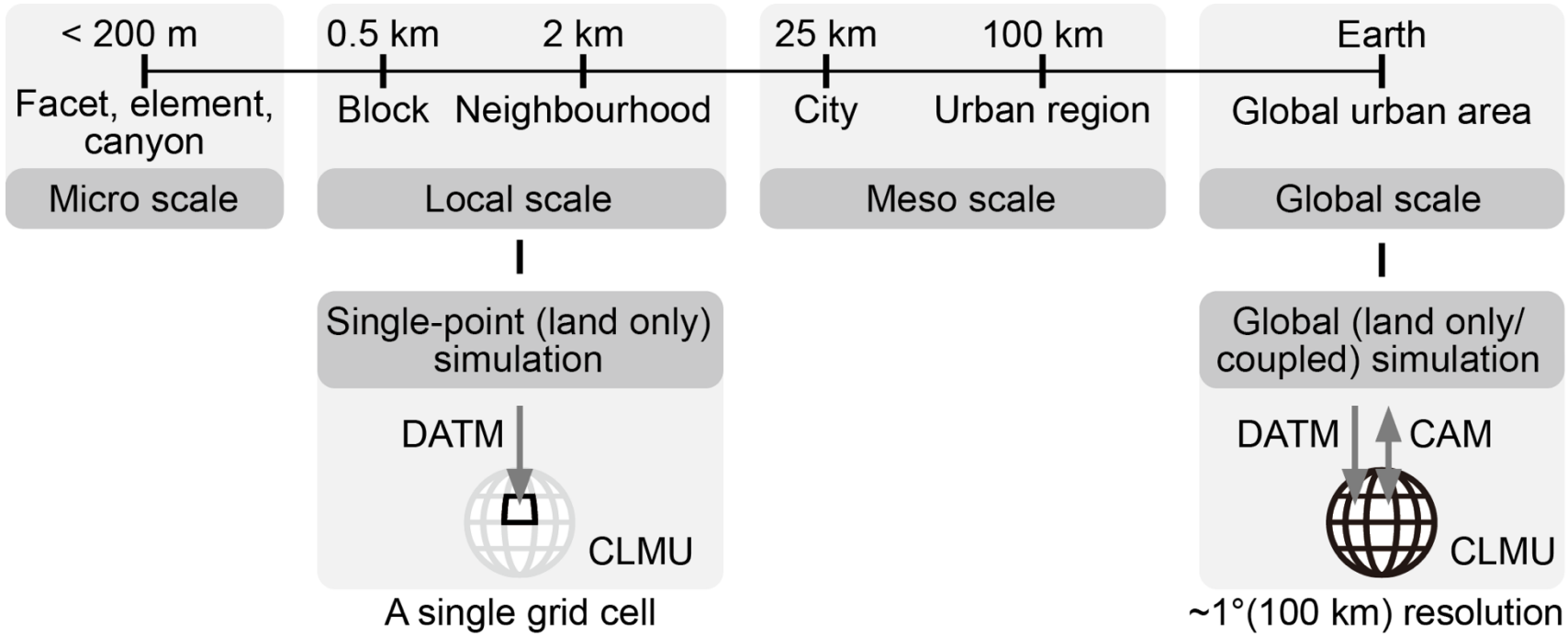
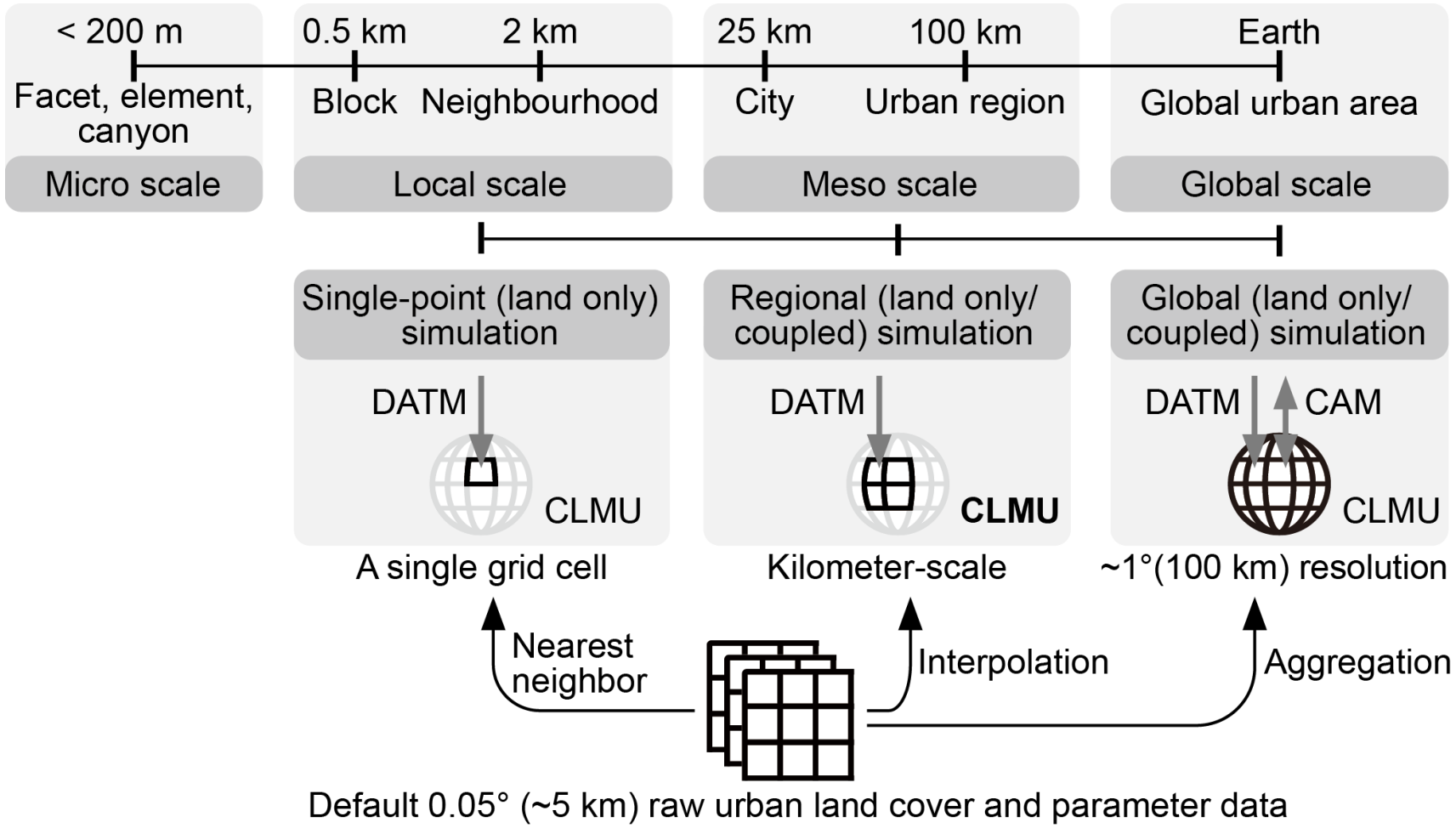


Fig. Capability of the CLMU in multi-scale urban climate modeling.

CTSM/CLMU capability: regional



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CTSM/CLMU capability: regional

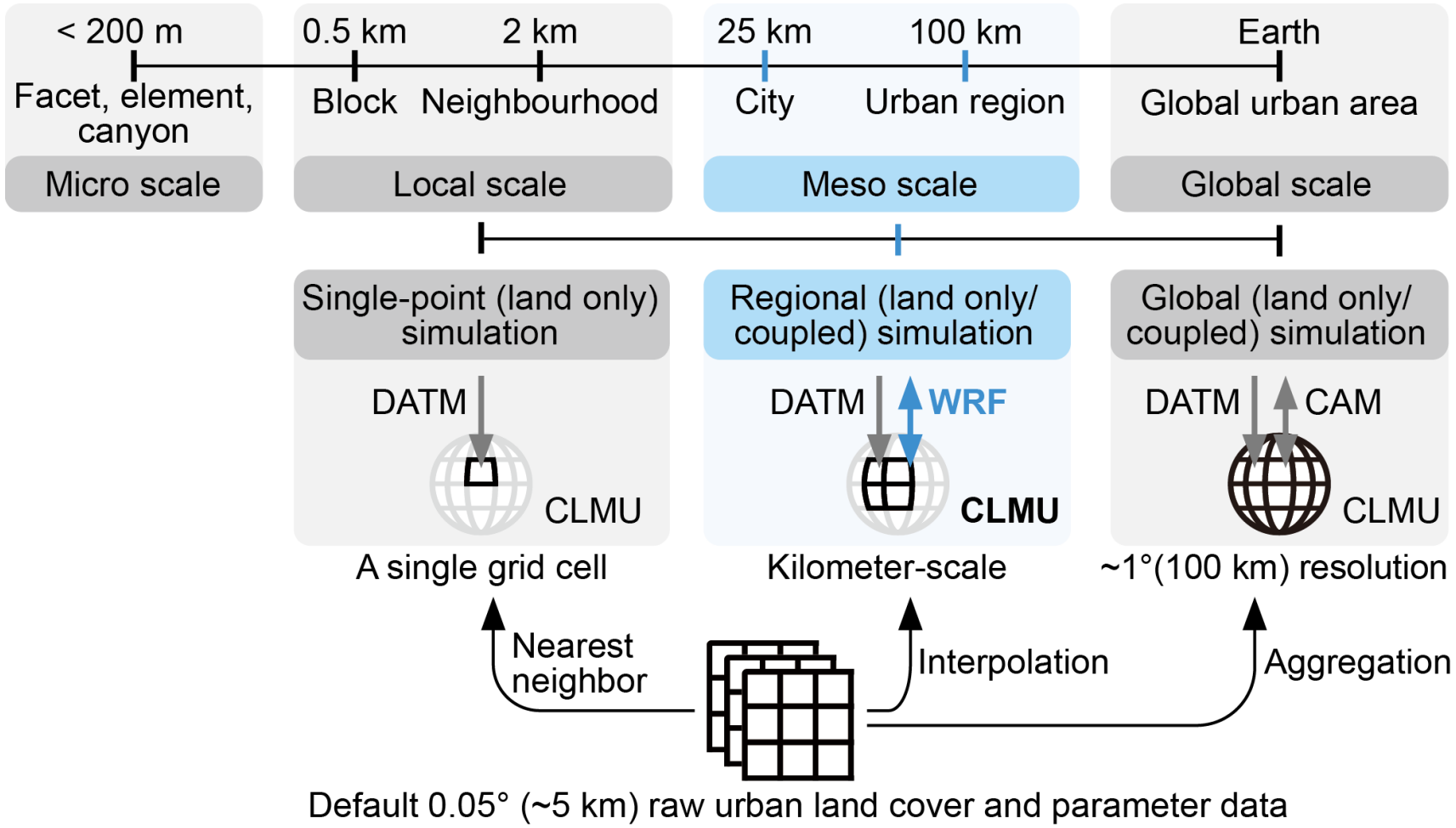


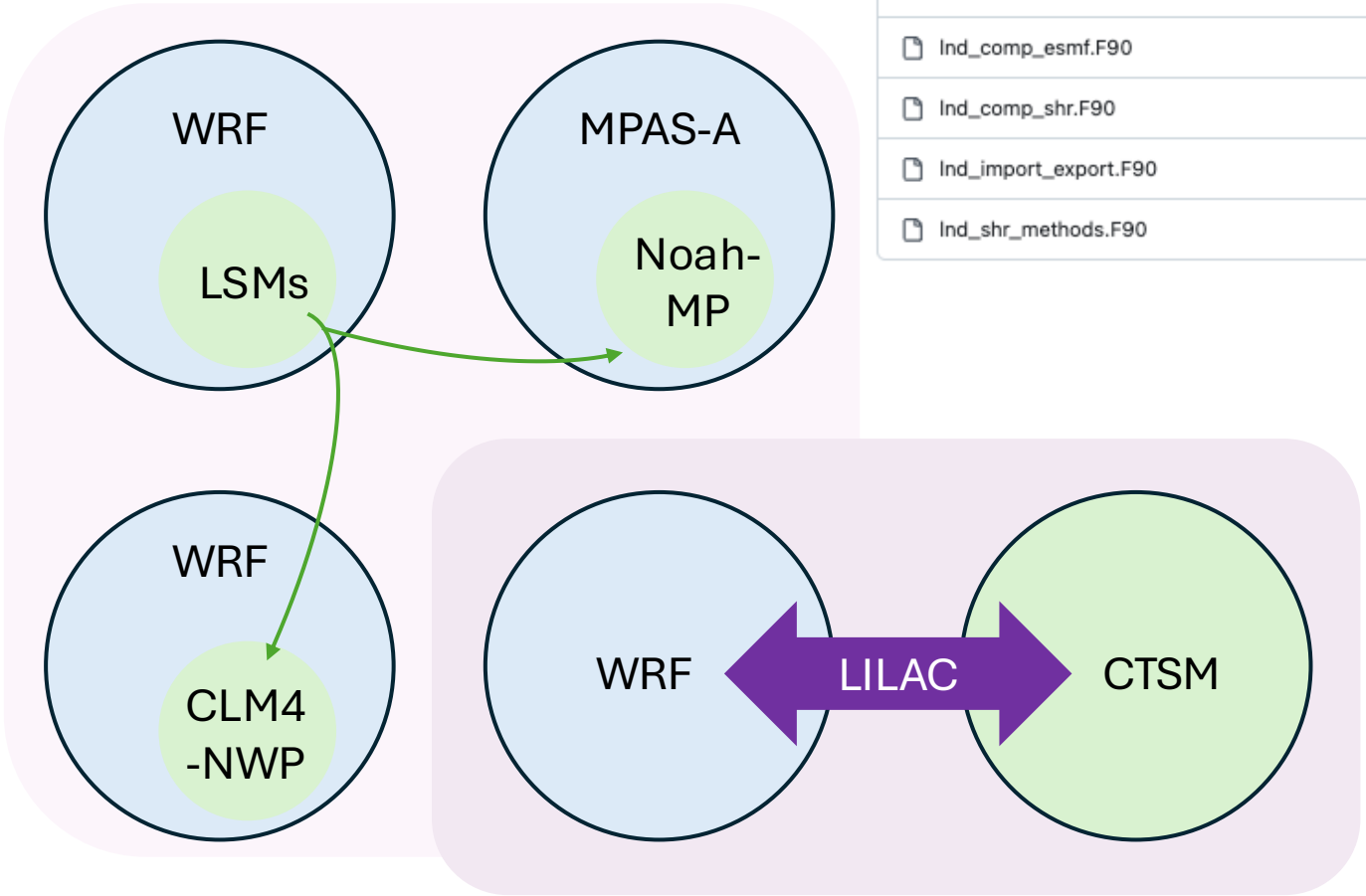
Fig. Capability of the CLMU in multi-scale urban climate modeling.

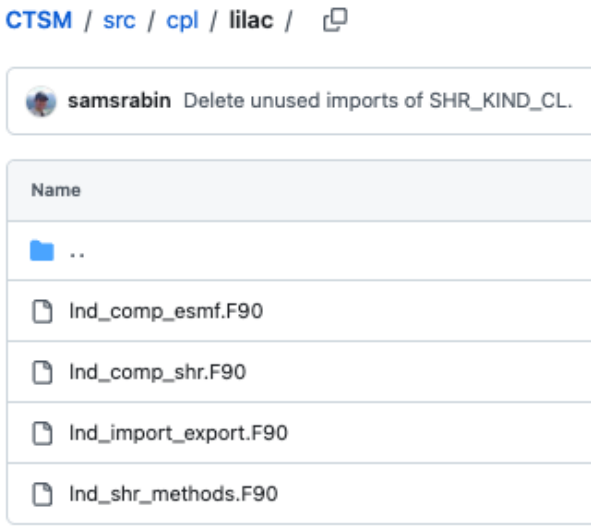
WRF-CTSM development

The Evaluation of Hydroclimatic Variables Over Nordic Fennoscandia Using WRF-CTSM

Iris Mužić[1,2], Øivind Hodnebrog[1], Yeliz A. Yilmaz[2], Terje K. Berntsen[2], David M. Lawrence[3], and Negin Sobhani[3]

Mužić et al (2025) conducted the first WRF-CTSM simulation at a grid spacing of 10.5 km.





Mužić et al. (2025). https://doi.org/ 10.1029/2024JD043103

https://github.com/wrf-model/WRF/blob/master/phys/module_sf_clm.F
https://github.com/wrf-model/WRF/blob/master/phys/module_sf_ctsm.F

https://github.com/ESCOMP/CTSM/tree/master/src/cpl/lilac

WRF-CLMU workflow development

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↓

Urban climate simulation requires finer spatial resolutions, for example, 1 km.

↓

Nested domains

Mužić et al. (2025). https://doi.org/ 10.1029/2024JD043103

WRF-CLMU workflow: ① WRF input

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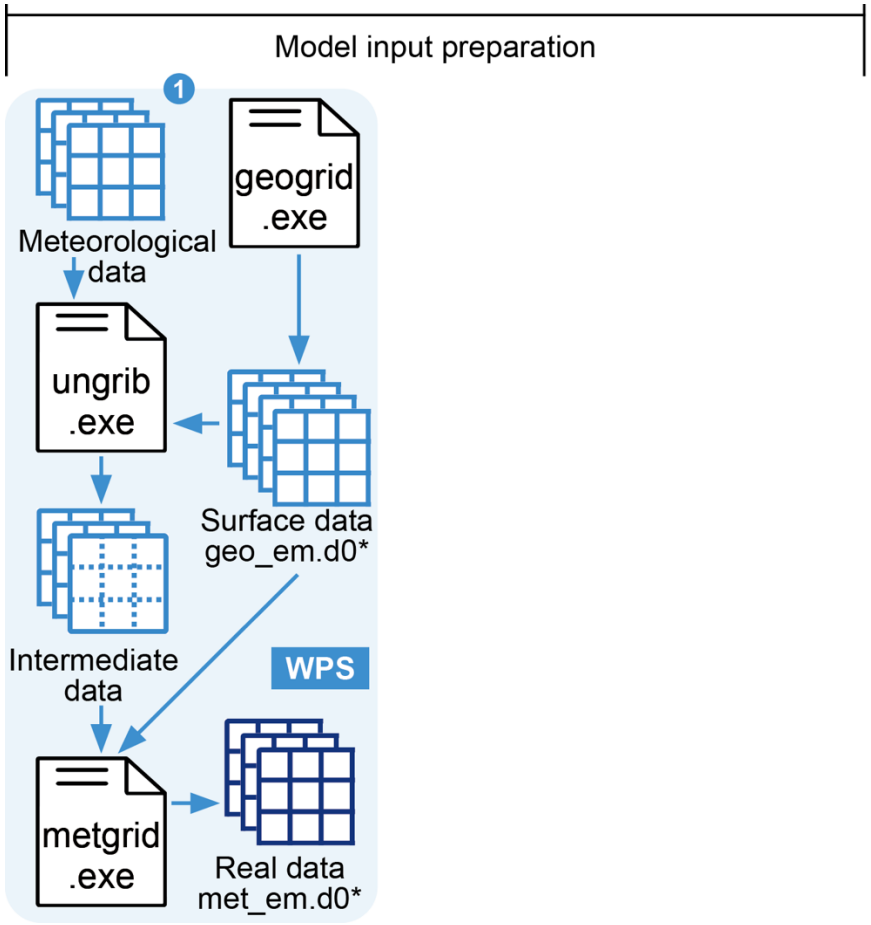

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Fig. General workflow of coupling the WRF and CTSM. The Lightweight Infrastructure for Land-Atmosphere Coupling (LILAC) serves as CTSM's interface with WRF.

WRF-CLMU workflow: ② WRF downscaling

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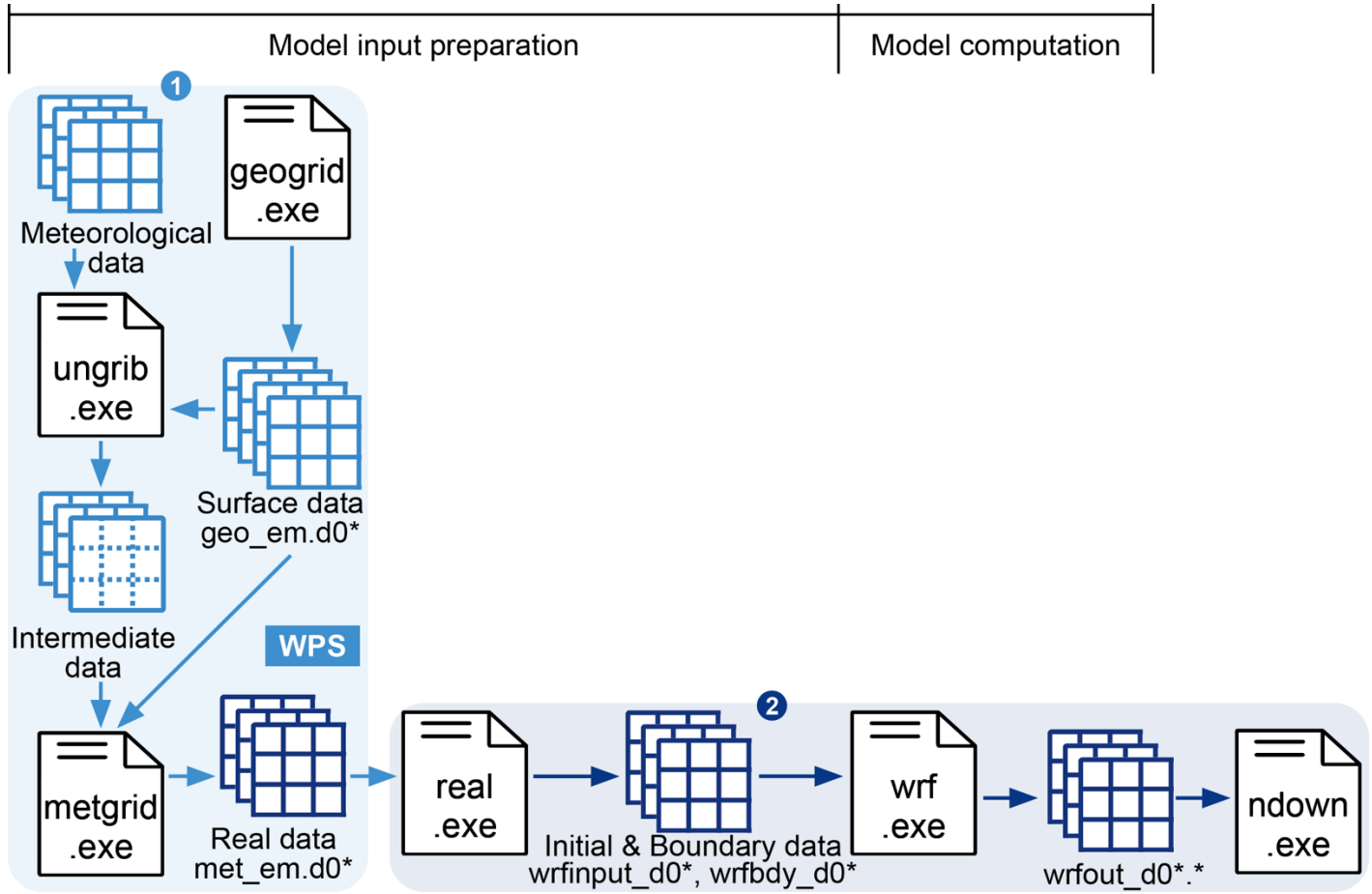

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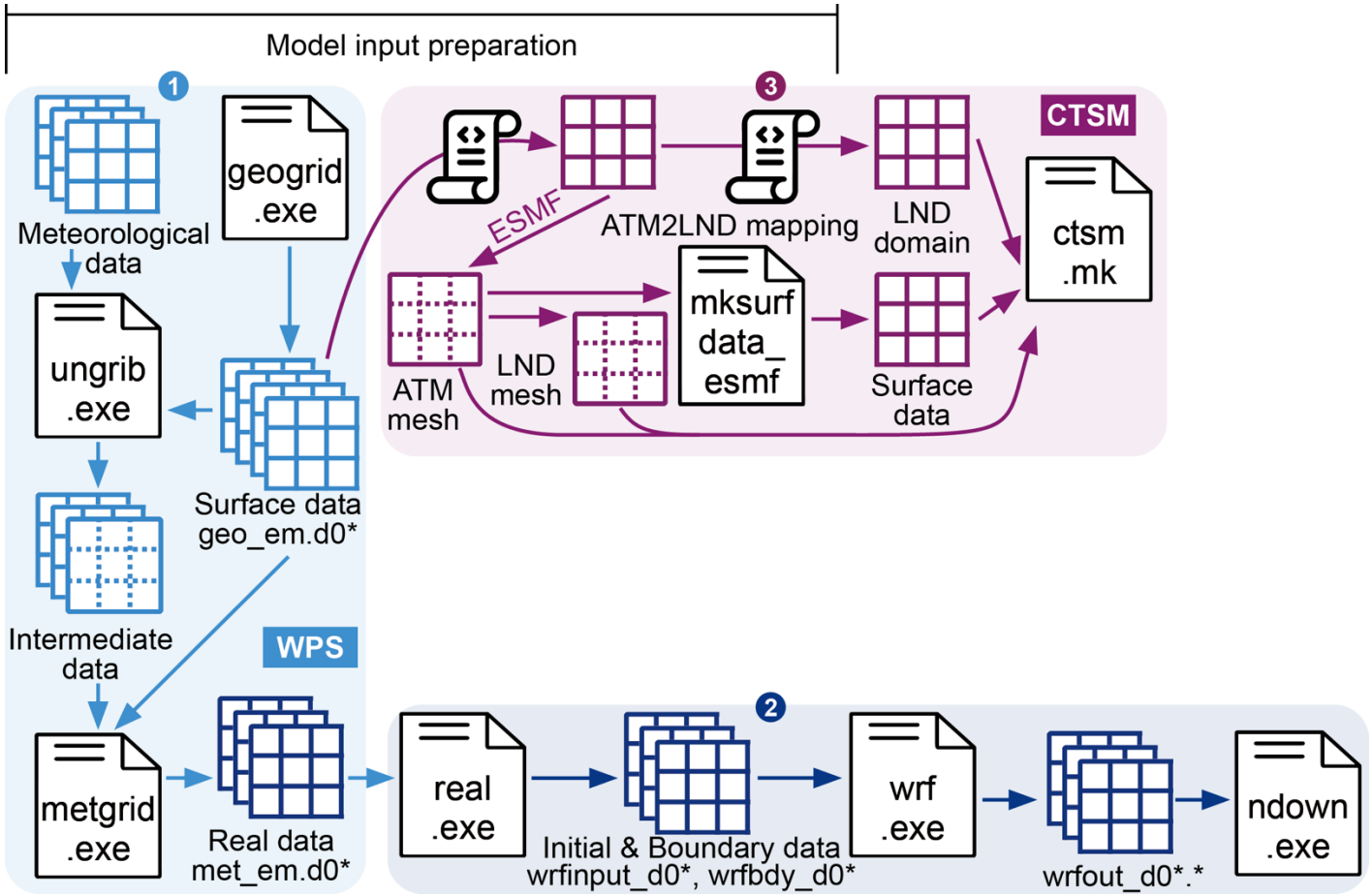

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WRF-CLMU workflow: ④ simulation

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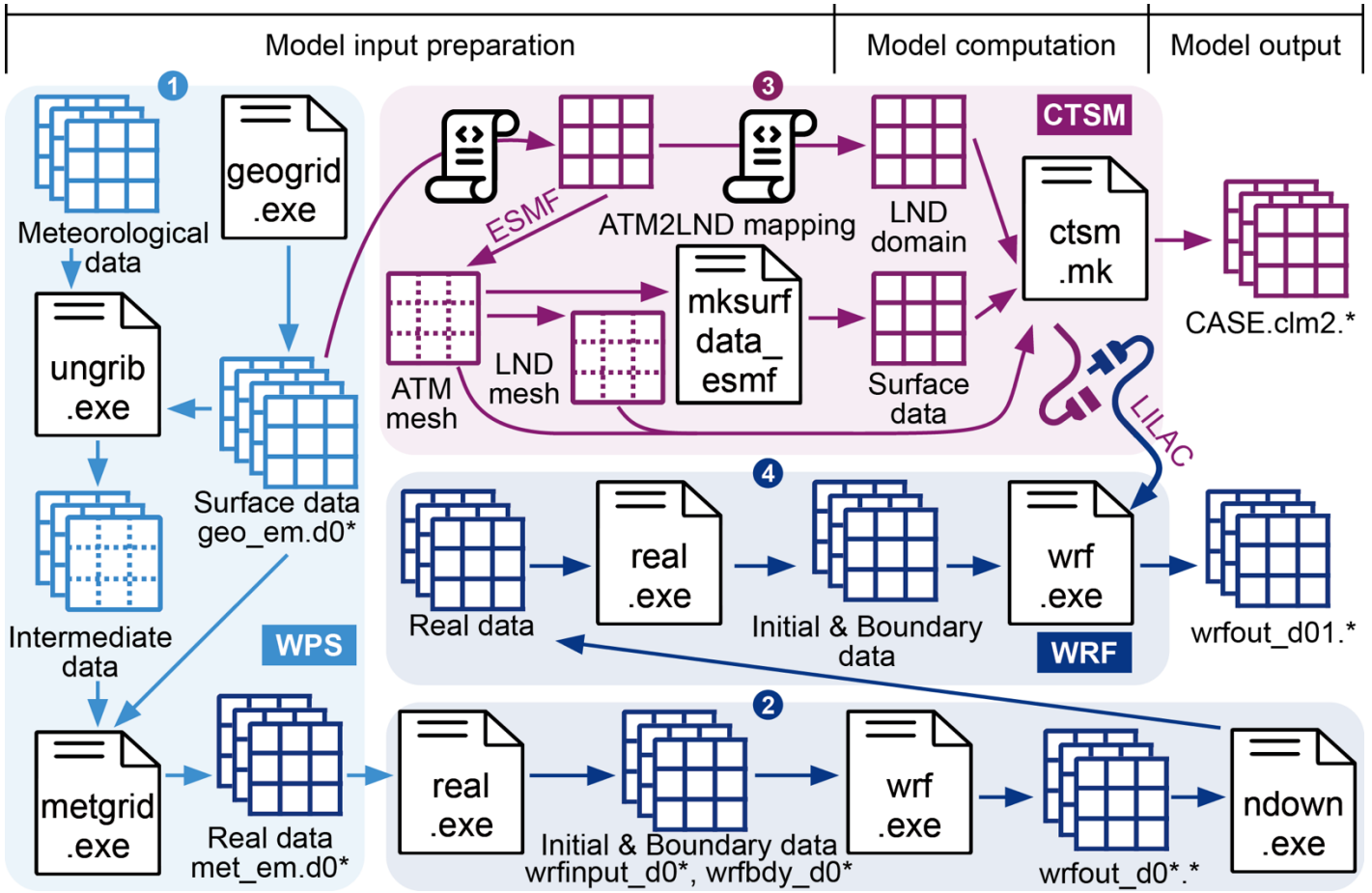

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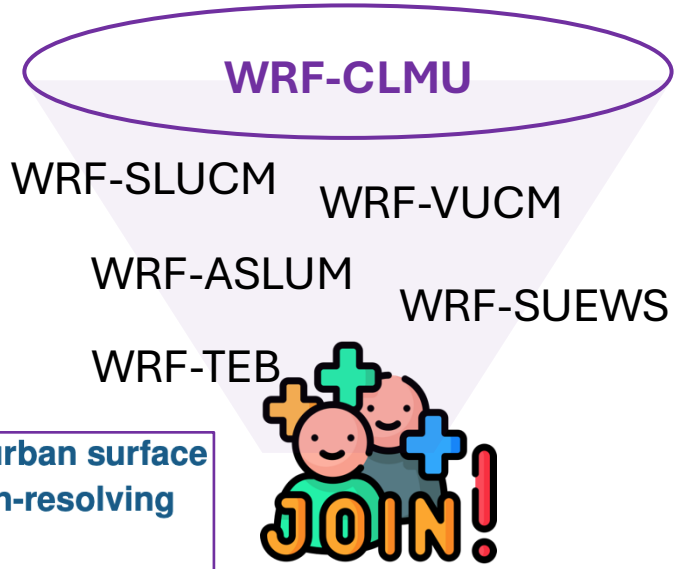
Advantages of WRF-CLMU

CLMU application: meso-scale urban climate simulations

- ✓ Enabling Atmosphere-land two-way interactions
  - Capturing atmospheric response to urban climate at fine resolutions
- ✓ Dynamic downscaling
  - Alleviating limitations of the availability and quality of meteorological forcing data
- ✓ Bringing post-CLMU5 development into full play
  - Explicit AC adoption
  - Transient urban representation
  - U-Surf, etc.

Model community: multi-model intercomparison



U-Surf: a global 1 km spatially continuous urban surface property dataset for kilometer-scale urban-resolving Earth system modeling

Yifan

Enhancing Global-Scale Urban Land Cover Representation Using Local Climate Zones in the Community Earth System Model

Yuan S
Matthia

Improving Urban Climate Adaptation Modeling in the Community Earth System Model (CESM) Through Transient Urban Surface Albedo Representation

Yuan Sun[1,2], Bowen Fang[3], Keith W. Oleson[4], Lei Zhao[3,5,6], David O. Topping[1], David M. Schultz[1,2], and Zhonghua Zheng[1,2]

Enhancing Urban Climate-Energy Modeling in the Community Earth System Model (CESM) Through Explicit Representation of Urban Air-Conditioning Adoption

Xinchang "Cathy" Li[1], Lei Zhao[1,2,3], Keith Oleson[4], Yuyu Zhou[5], Yue Qin[6], Keer Zhang[7], and Bowen

Urban Land Expansion Amplifies Surface Warming More in Dry Climate than in Wet Climate: A Global Sensitivity Study

Keer Zhang[1,2], Bowen Fang[3], Keith Oleson[4], Lei Zhao[3], Chunyang He[5,6], Qingxu Huang[5,6], Zhifeng Liu[5,6], Chang Cao[7], and Xuhui Lee[1]

Simplified CTSM settings for numerical weather prediction (NWP)

Configuration	Long name	standard	fast	Influence on urban climate simulation
soil_layerstruct_predefined	Soil layers and depth	20-layer soil column, 8 m of soil, 5 bedrock layers	4-layer soil column, 2 m of soil, 0 bedrock layers	Energy and water processes on urban pervious floor
itmax_canopy_fluxes	Maximum number of iterations used for canopy fluxes	40	3	Urban canopy thermal conditions
nlevsno	Number of snow layers	12	5	Urban snow and related hydrologic processes
h2osno_max	Maximum snow depth in H2O equivalent	10000.0 mm	5000.00 mm	Urban snow and related hydrologic processes
collapse_urban	Represent urban land cover by a dominant urban land-unit	.false.	.true.	Representation of urban land cover heterogeneity
n_dom_landunits	Represent land cover by a dominant land-unit	.false.	.true.	Representation of urban areal fraction
n_dom_pfts	Number of dominant plant functional types (PFTs)	0 (Using all PFTs)	1 (Using 1 PFTs)	No direct impacts on urban areas, but indirectly influences urban–rural climate contrast through changes in rural land representation

We recommend changing ***n_dom_landunits = .false.*** for WRF-CLMU.

Nested domains

- D01: 32.4 km
- D02: 10.8 km
- D03: 3.6 km
- D04: 1.2 km

3:1

3:1

3:1

WRF simulation for dynamic downscaling

WRF-CLMU simulation

Model and domain	Simulation name	Simulation period
WRF with d04	GM_SLUCM	25 Dec 2021 to 31 Dec 2022
WRF-CTSM with d04	GM_CLMU	

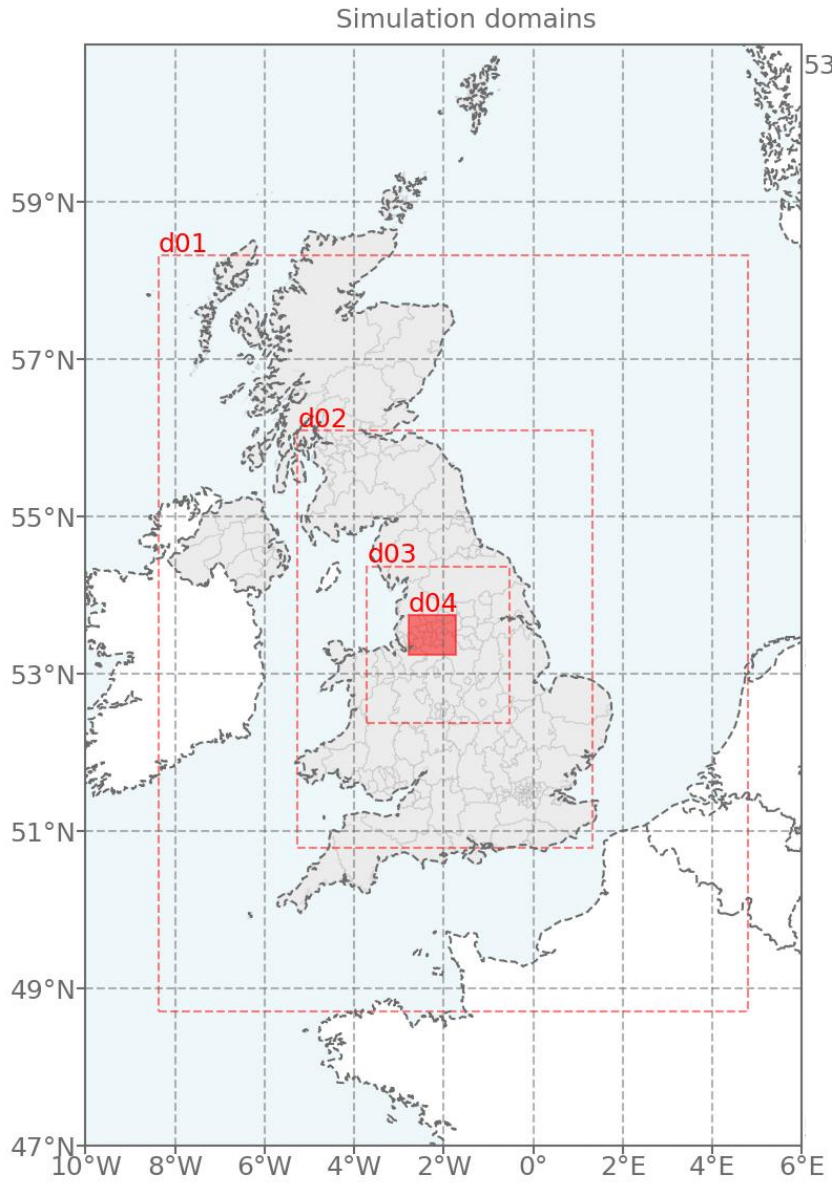


Fig. Case study area: Greater Manchester, UK (d04).

Comparing model performance of WRF-CLMU and WRF-SLUCM with in-situ observations

		HadISD (2 m)		MAQS (7 m)		Whitworth (53 m)	
		GM_SLUCM	GM_CLMU	GM_SLUCM	GM_CLMU	GM_SLUCM	GM_CLMU
Air temperature (°C)	MAE	1.13	1.23	1.14	1.17	1.06	1.03
	MBE	-0.23	-0.56	0.12	-0.22	0.18	0.23
	RMSE	1.51	1.58	1.52	1.50	1.46	1.34
	NSTD	1.03	1.06	1.07	1.07	1.09	1.05
	R	0.97	0.97	0.97	0.97	0.97	0.98
	5th	0.35	0.51	0.78	0.21	1.01	0.75
	95th	0.90	1.86	0.37	1.26	0.51	0.46
	SKEW	0.17	1.42	0.98	0.35	1.09	0.02
	KURTOSIS	0.40	0.61	0.26	0.74	0.19	0.41
	PSS	0.53	0.53	0.07	0.08	0.06	0.06
Relative humidity (%)	MAE	8.87	9.11	8.98	9.11	7.49	7.51
	MBE	5.57	6.31	7.05	7.01	1.54	0.07
	RMSE	11.82	12.06	11.36	11.44	9.71	9.63
	NSTD	1.03	1.05	1.12	1.11	1.01	0.95
	R	0.81	0.82	0.86	0.86	0.80	0.79
	5th	3.21	5.88	7.13	8.59	0.13	1.03
	95th	1.57	5.45	0.61	3.67	0.94	5.20
	SKEW	0.42	0.16	0.56	0.31	0.26	0.69
	KURTOSIS	20.49	17.35	2.68	2.41	0.08	0.07
	PSS	0.59	0.63	0.21	0.17	0.11	0.12
Wind speed (m/s)	MAE	1.87	1.37	2.86	1.70	1.72	1.23
	MBE	-1.60	-0.62	-2.83	-1.60	-1.47	-0.48
	RMSE	2.32	1.80	3.42	2.23	2.19	1.61
	NSTD	1.17	1.11	2.79	2.30	1.45	1.30
	R	0.73	0.71	0.71	0.68	0.83	0.80
	5th	0.47	0.25	0.31	0.22	0.08	0.20
	95th	1.80	0.78	5.53	3.86	3.14	1.99
	SKEW	0.67	0.59	0.55	0.32	0.42	0.20
	KURTOSIS	0.96	1.10	0.92	0.92	0.89	0.85
	PSS	0.68	0.68	0.63	0.38	0.27	0.15

MAE: Mean absolute error

MBE: Mean absolute error

RMSE: Root mean square error

NSTD: Normalized standard deviation

R: Correlation coefficient

5th percentile absolute bias error

95th percentile absolute bias error

SKEW: Skewness

KURTOSIS: Kurtosis

PSS: Probability of smallest spread

Better performance

Fig. Evaluation of hourly variables using performance metrics from GM_SLUCM and GM_CLMU simulations.

Comparing model performance of WRF-CLMU and WRF-SLUCM with in-situ observations

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	KURTOSIS	0.40	0.61	0.26	0.74	0.19	0.41
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5th percentile absolute bias error
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Better performance

WRF-CLMU performs better at Whitworth and MAQS stations, while worse at HadISD.

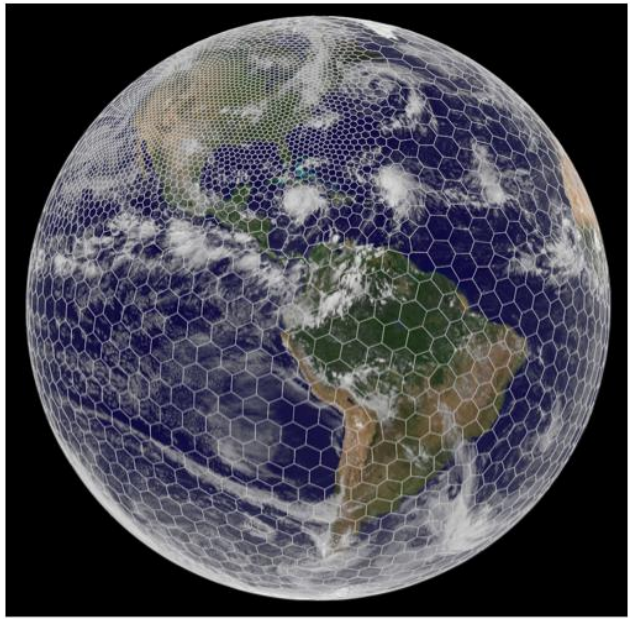
The HadISD station is located at Manchester airport with little dense built-up. WRF-CLMU is likely to overestimate the urban thermal impact.

Fig. Evaluation of hourly variables using performance metrics from GM_SLUCM and GM_CLMU simulations.

Summary

- This study demonstrates the capability of the CLMU via WRF coupling for high-resolution urban climate simulations.
- Future work
  - Model evaluation at more urban sites.
  - An ensemble approach to examining model sensitivity to different atmospheric schemes.
  - Apply WRF-CLMU with CLMU's newly-developed functionalities.
- MPAS-CTSM
  - For next-generation land-atmosphere coupling?
  - How could *mksurfdata_esmf* adapt to an unstructured Voronoi mesh?

Preprint



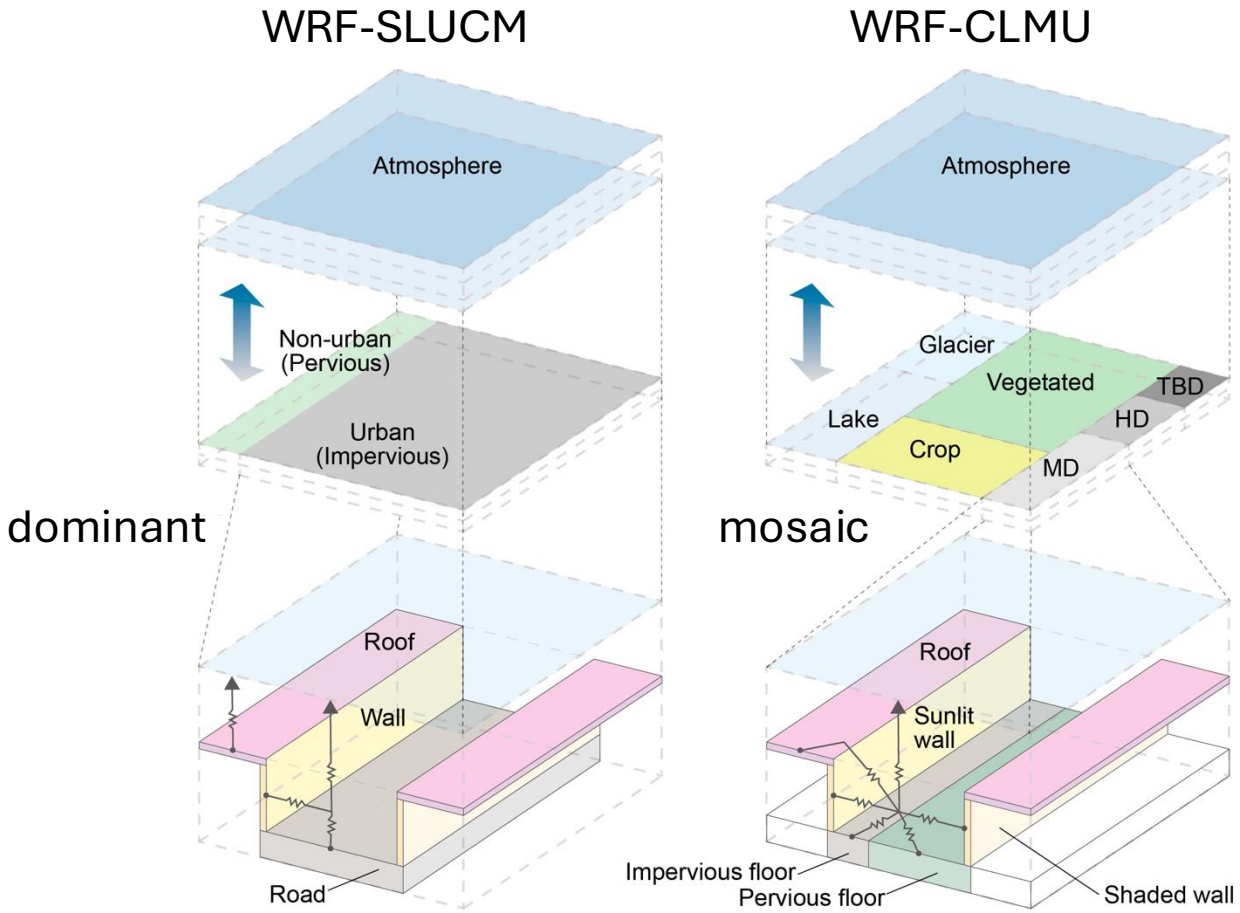
MAPS: Voronoi mesh

Thanks! Any questions or comments?

Figure source: https://mpas-dev.github.io

Contact us: yuan.sun@manchester.ac.uk, oleson@ucar.edu, cenlinhe@ucar.edu, zhonghua.zheng@manchetser.ac.uk

Why we need WRF-CLMU besides WRF default urban schemes?



As an urban climate model developed for Earth system modeling, CLMU represents physical processes more explicitly than SLUCM, which is designed primarily for numerical weather prediction.

Fig. Urban representation in land surface models.

Comparing model performance of WRF-CLMU and WRF-SLUCM with remote-sensing products

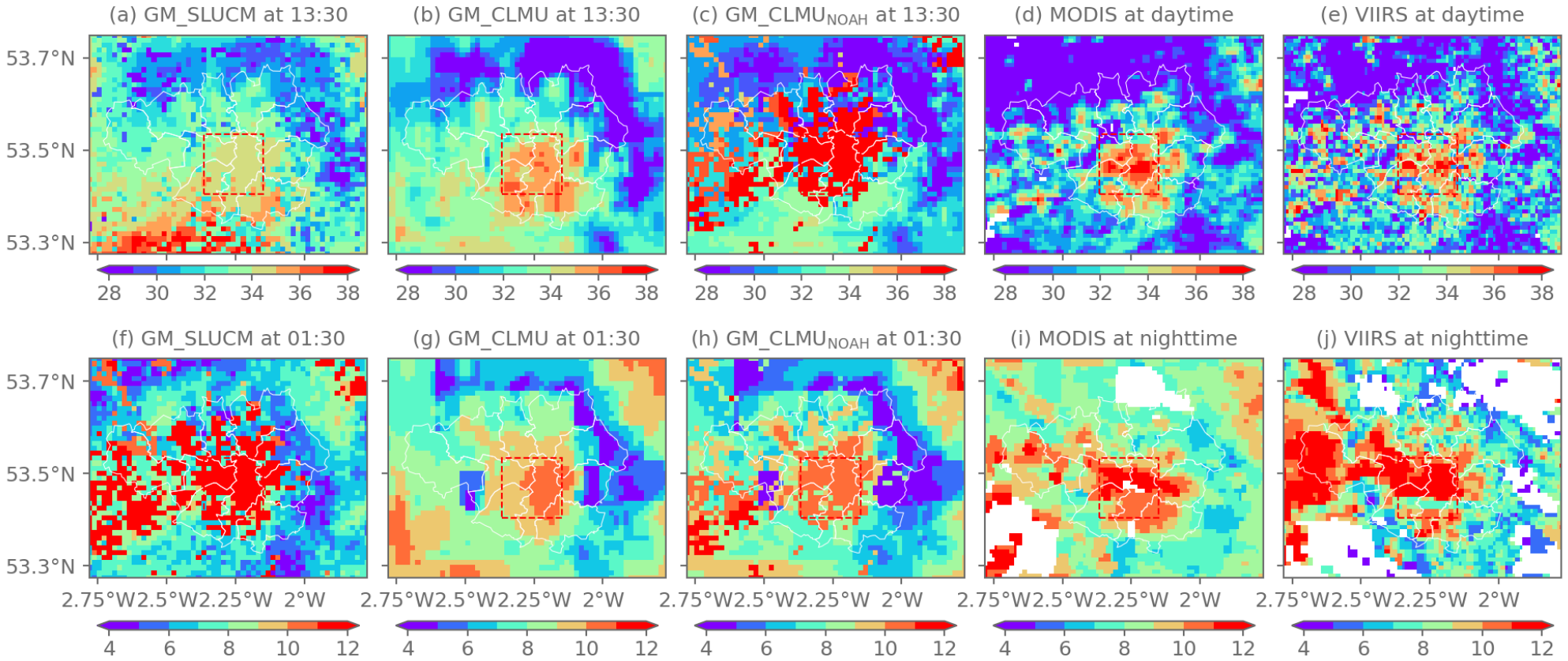
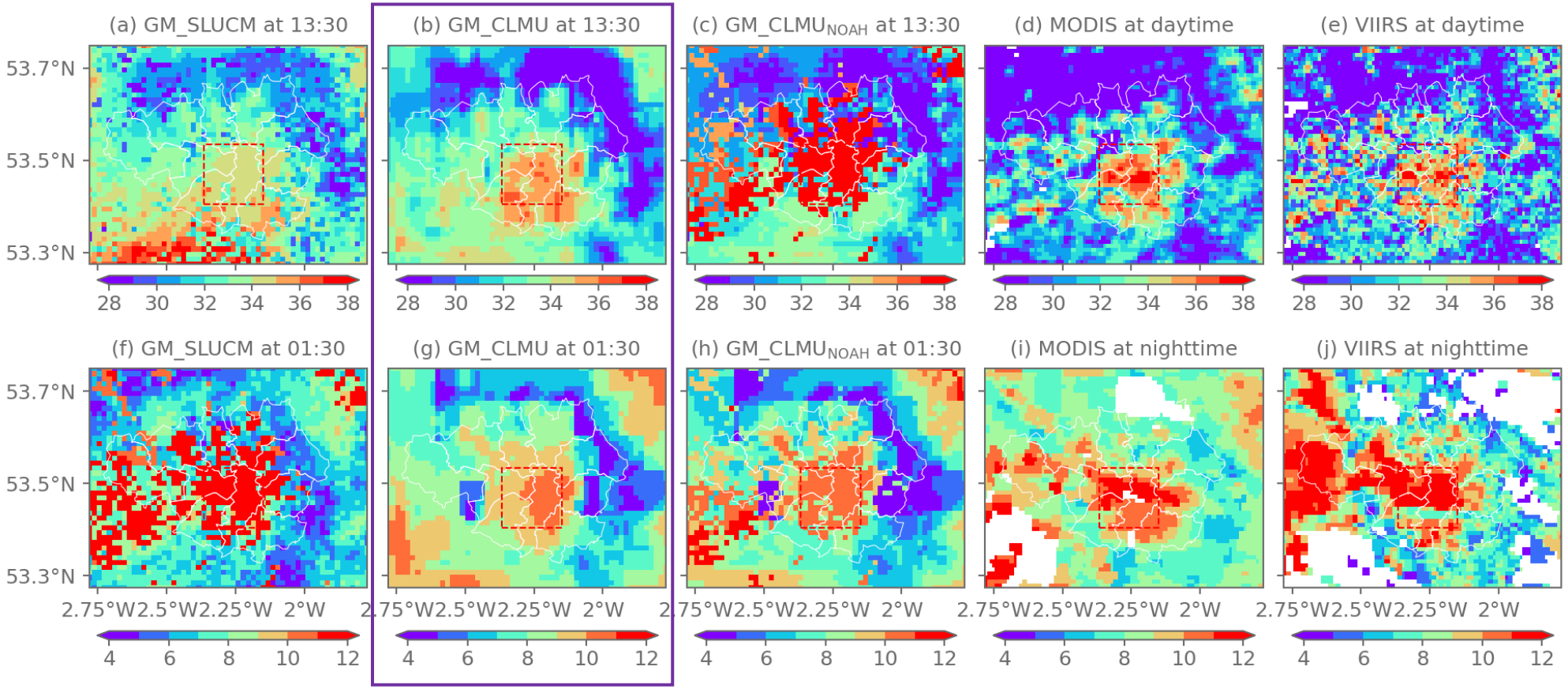


Fig. Land surface temperature (LST) on 16 July 2022, marking the onset of the July heatwave.

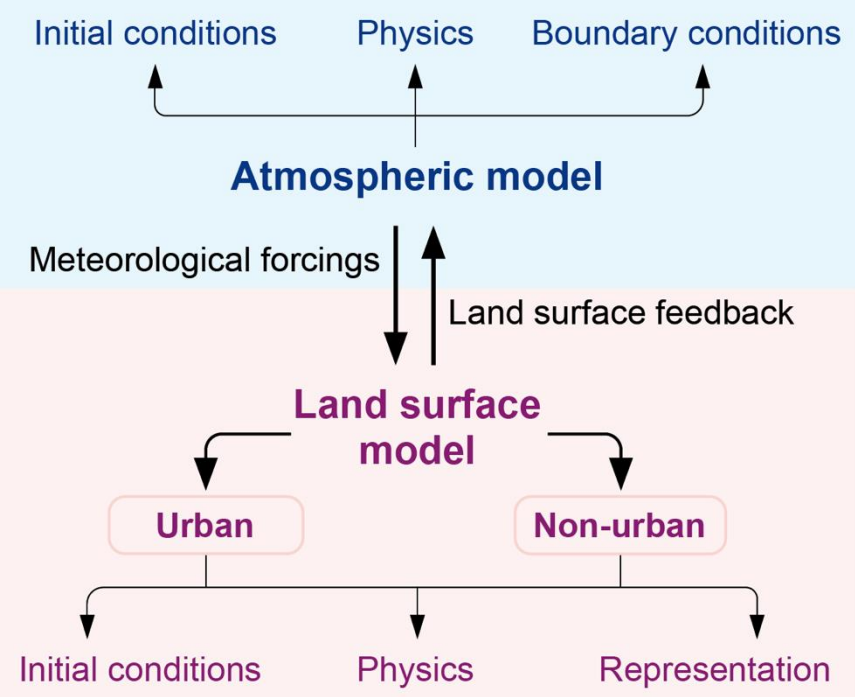
Comparing model performance of WRF-CLMU and WRF-SLUCM with remote-sensing products

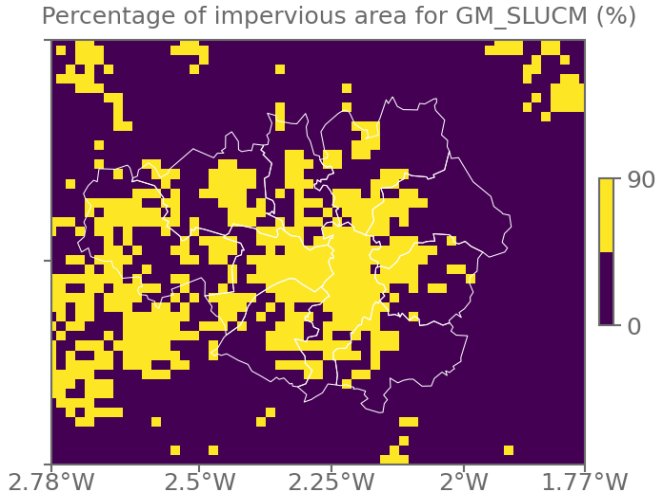


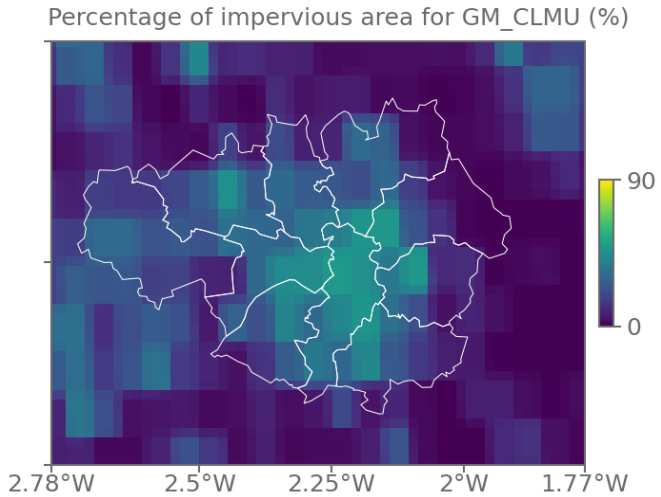
Compared to GM_SLUCM, LST in GM_CLMU is higher during the day and lower at night.

Fig. Land surface temperature (LST) on 16 July 2022, marking the onset of the July heatwave.

Differences raised from multiple factors







- GM_CLMU represents less impervious area, resulting in less daytime heat storage and nighttime release.
- CLMU models the urban pervious floor as bulk soil, overestimating temperature regardless of urban vegetation effects.

Fig (left). Illustration of factors contributing to simulation differences.
Fig (right). Percentage of impervious area.

Discussion: computational constraint

- WRF-CLMU is somewhat limited by computational cost.
  - Although finer spatial resolution reduces the CPU requirements on the WRF side, running CTSM remains demanding, and a small number of CPUs is insufficient because the CTSM is computationally heavy.

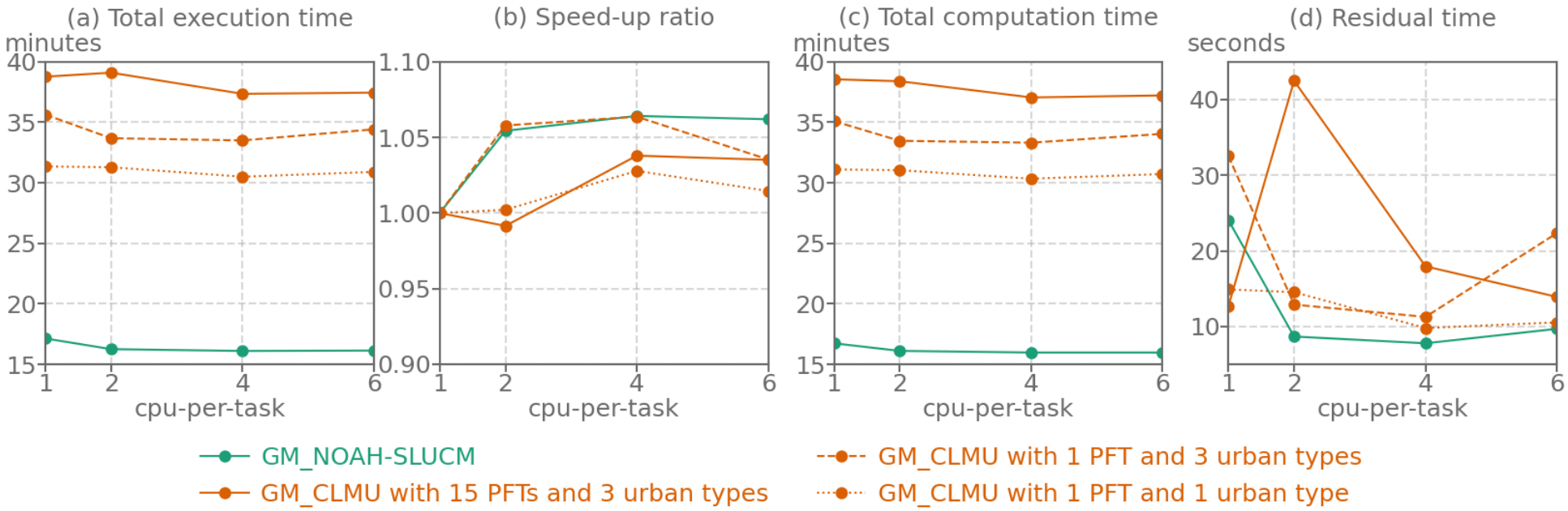


Fig. Timing of GM_SLUCM and GM_CLMU simulations. PFT is the plant functional type.