Introduction to WRF

Andrea Zonato, University of Trento

Where is Trento?

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But we even do research!
Mountain meteorology, turbulence in complex terrain, pollutant dispersion, agrometeorology, urban meteorology...

What is WRF?

Weather **R**esearch and **F**orecasting model

- ✓ Developed by the National Center for Atmospheric Research (NCAR) in Boulder, Colorado
- ✓ Community model, i.e. free, open source resource developed by **providers** and **users** (GitHub!)
- ✓ Version 1.0 released in December 2000 →Version 4.4 released in April 2022
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What is WRF?

WRF is a **Mesoscale** Numerical Weather Prediction (NWP) model

- ✓ Designed to perform **regional** simulations (from ~ 10 km to ~ 10 m)
- ✓ Allows nesting for higher resolution in the region of interest
- ✓ Can produce simulations from global observations, analyses, and re-analyses
- ✓ Designed as a **dynamycal core** (advection, pressure gradients, diffusion, time-stepping, ...) + **physical parameterizations**

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What is used for?

A tool for **weather forecasts**:

- ✓ **Operational** forecasting
- ✓ Hind-casting
- ✓ Forecasting for wind/solar energy and air quality

A tool for **research**:

- ✓ Developing and testing **physical parameterizations**
- ✓ **Idealized** simulations of a large spectra of case studies
- ✓ Case study research for particular weather events

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WRF Flavors:

Various WRF packages for different applications:

- ✓ **WRF-Chem**: chemistry packages for air quality/aerosol applications
- ✓ **WRF-Fire**: WRF for understanding/predicting wildfires
- ✓ **WRF-4DVAR**: WRF for improving forecasts through data assimilation
- ✓ **WRF-Hydro**: Coupling between WRF and hydrology modules
- ✓ **WRF-Solar**: WRF Optimization for Solar Energy forecasts

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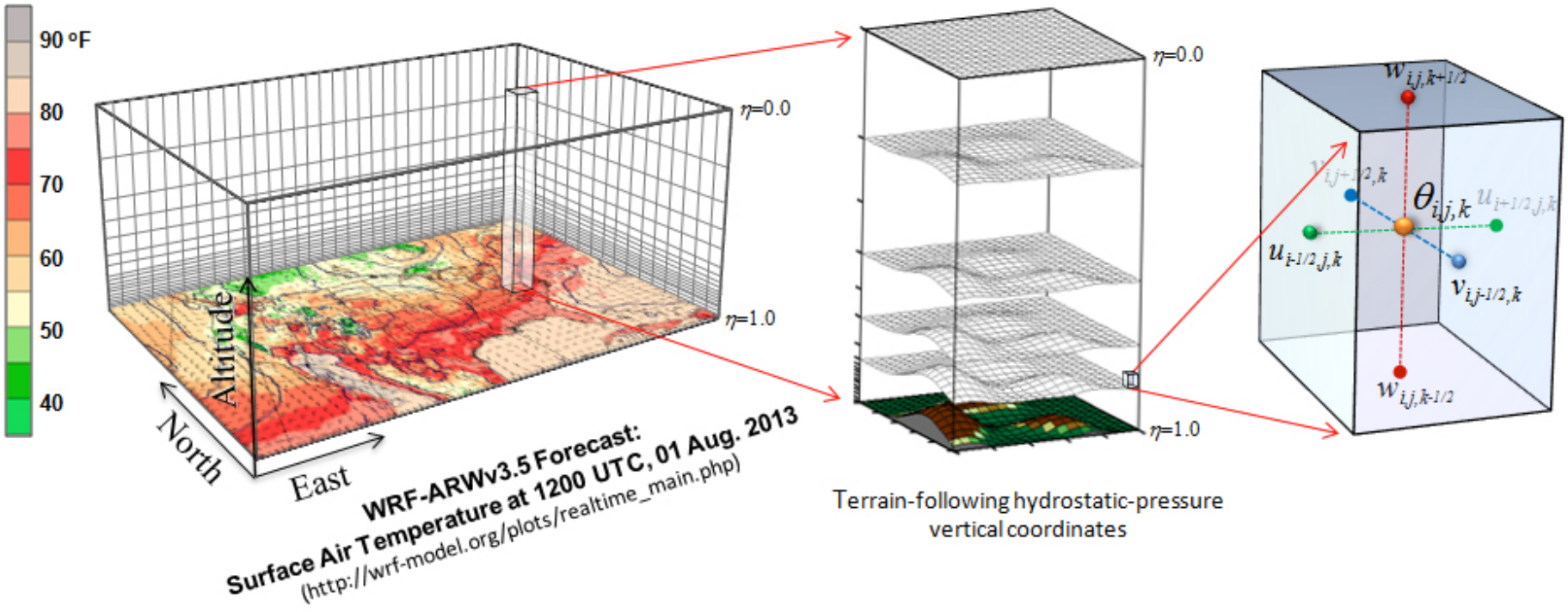
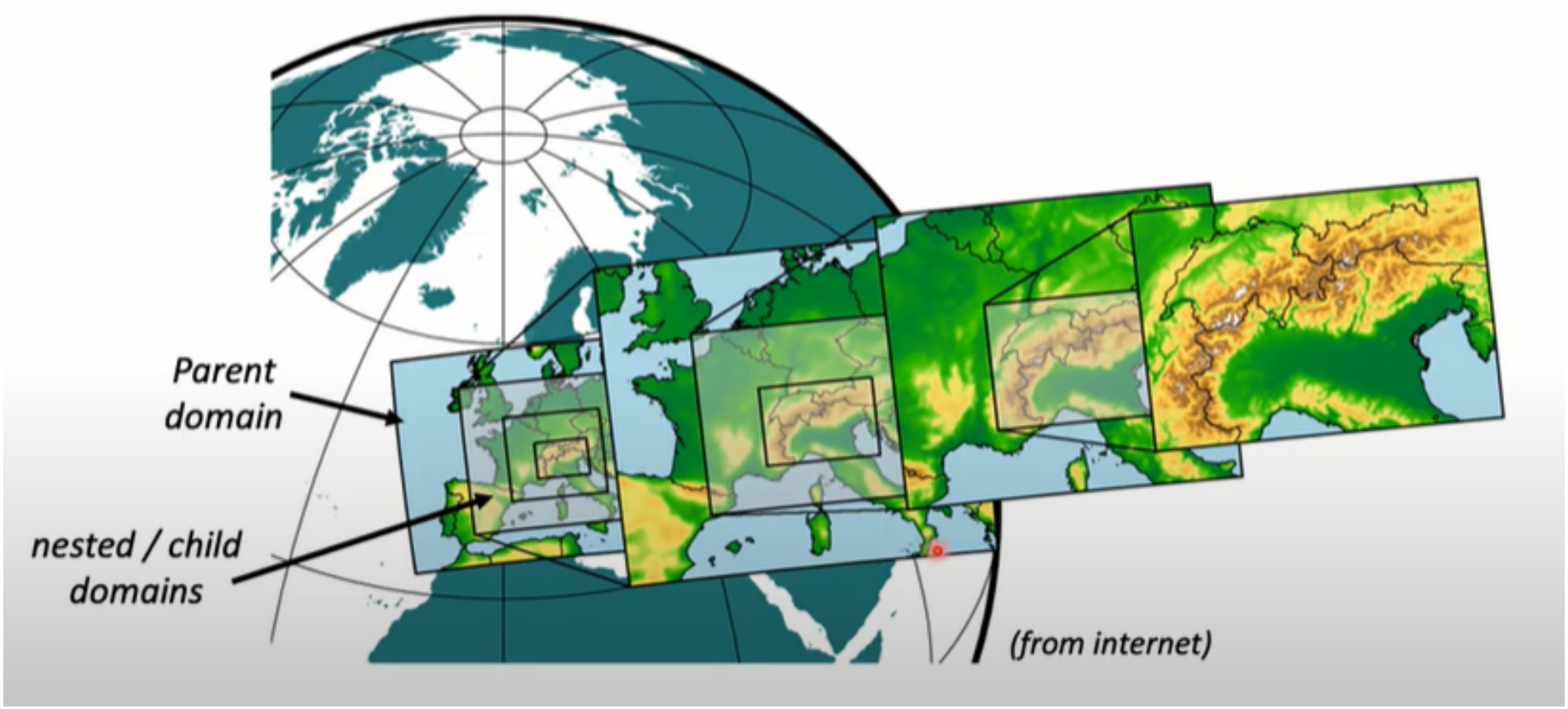
How a NWP model works?



The dynamical core (solving Navier-Stokes equations)

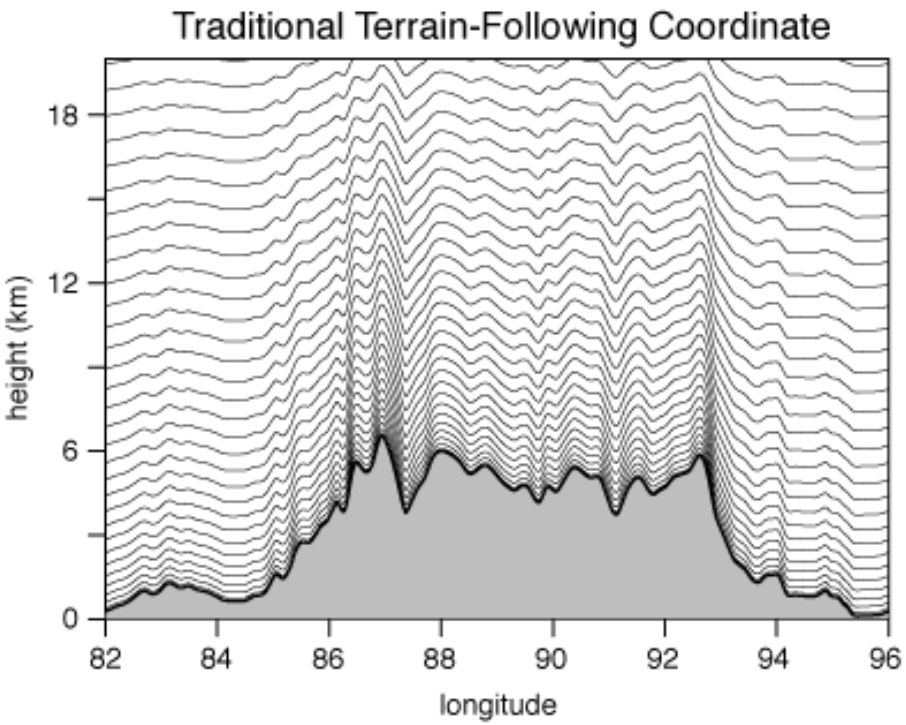
$$
\begin{aligned}
\partial_t U + (\nabla \cdot \mathbf{V}u) + \mu_d \alpha \partial_x p + (\alpha/\alpha_d)\partial_\eta p \partial_x \phi &= F_U \\
\partial_t V + (\nabla \cdot \mathbf{V}v) + \mu_d \alpha \partial_y p + (\alpha/\alpha_d)\partial_\eta p \partial_y \phi &= F_V \\
\partial_t W + (\nabla \cdot \mathbf{V}w) - g[(\alpha/\alpha_d)\partial_\eta p - \mu_d] &= F_W \\
\partial_t \Theta_m + (\nabla \cdot \mathbf{V}\theta_m) &= F_{\Theta_m} \\
\partial_t \mu_d + (\nabla \cdot \mathbf{V}) &= 0 \\
\partial_t \phi + \mu_d^{-1}[(\mathbf{V} \cdot \nabla \phi) - gW] &= 0 \\
\partial_t Q_m + (\nabla \cdot \mathbf{V}q_m) &= F_{Q_m} \\
\partial_\eta \phi &= -\alpha_d \mu_d \\
p &= p_0 \left(\frac{R_d \theta_m}{p_0 \alpha_d} \right)^\gamma
\end{aligned}
$$

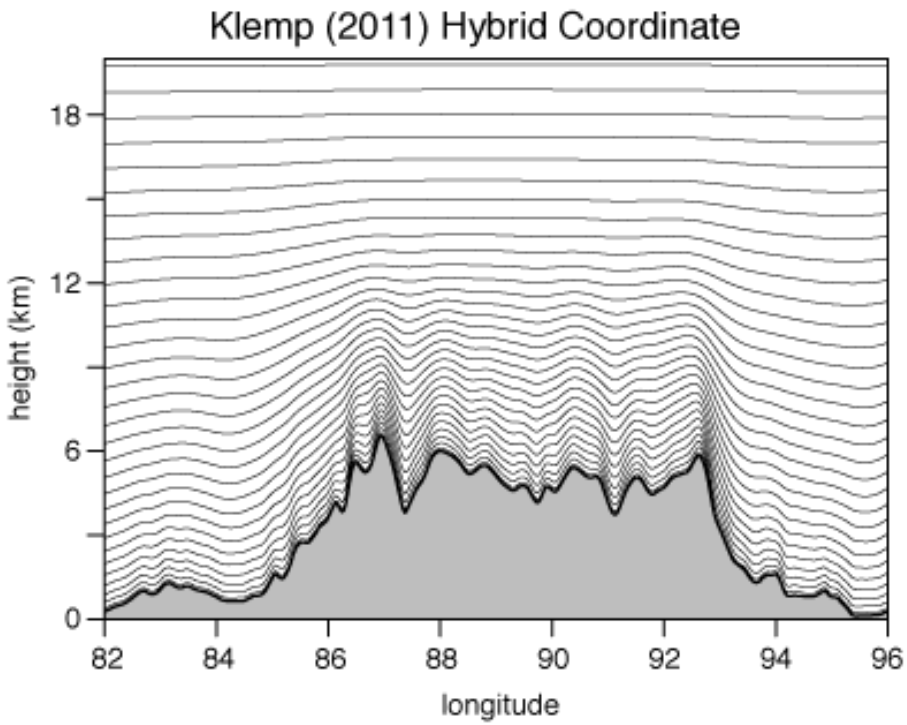
How the nesting work? (From $\sim$ 50 km to $\sim$ 1 km)



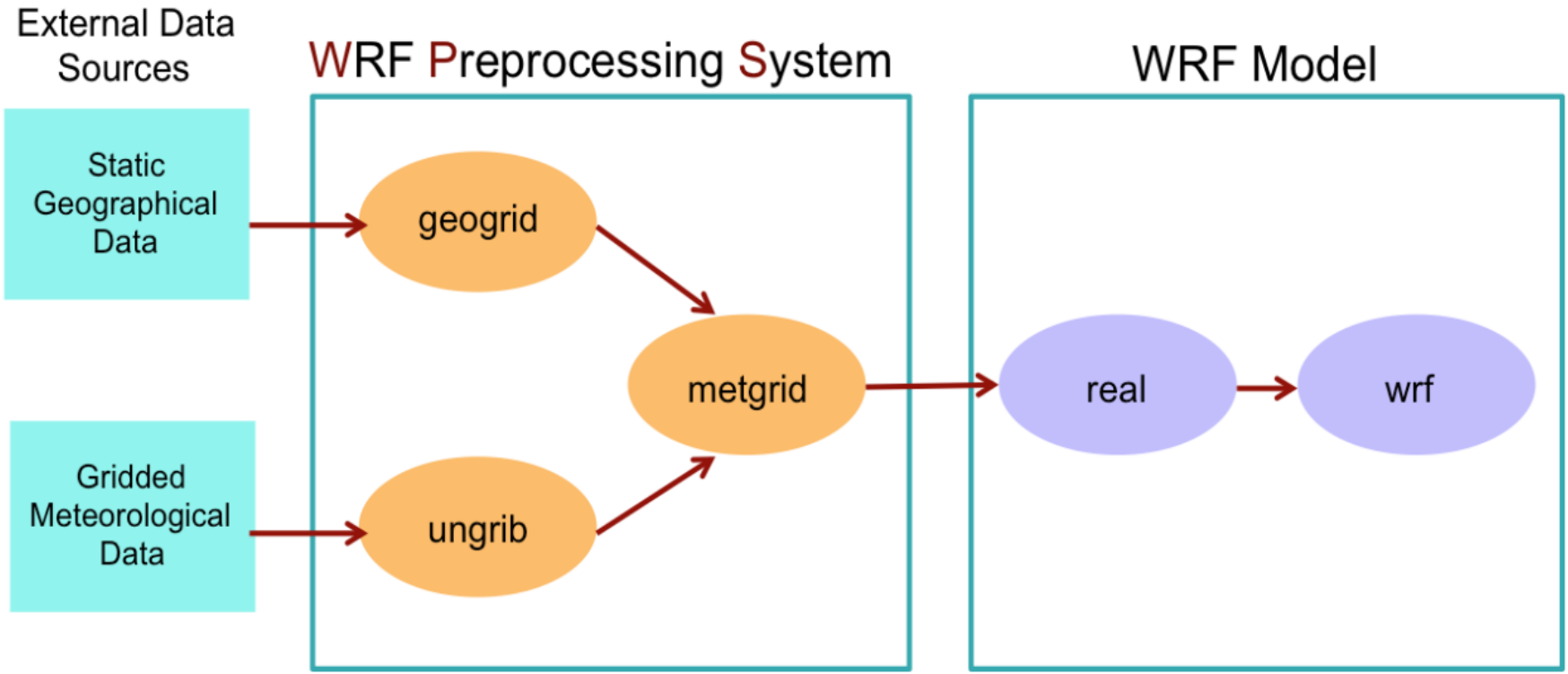
Vertical coordinates - Terrain following

$$\eta = \frac{p^h - p^h_{top}}{p^h_0 - p^h} \qquad 0 \leq \eta \leq 1$$





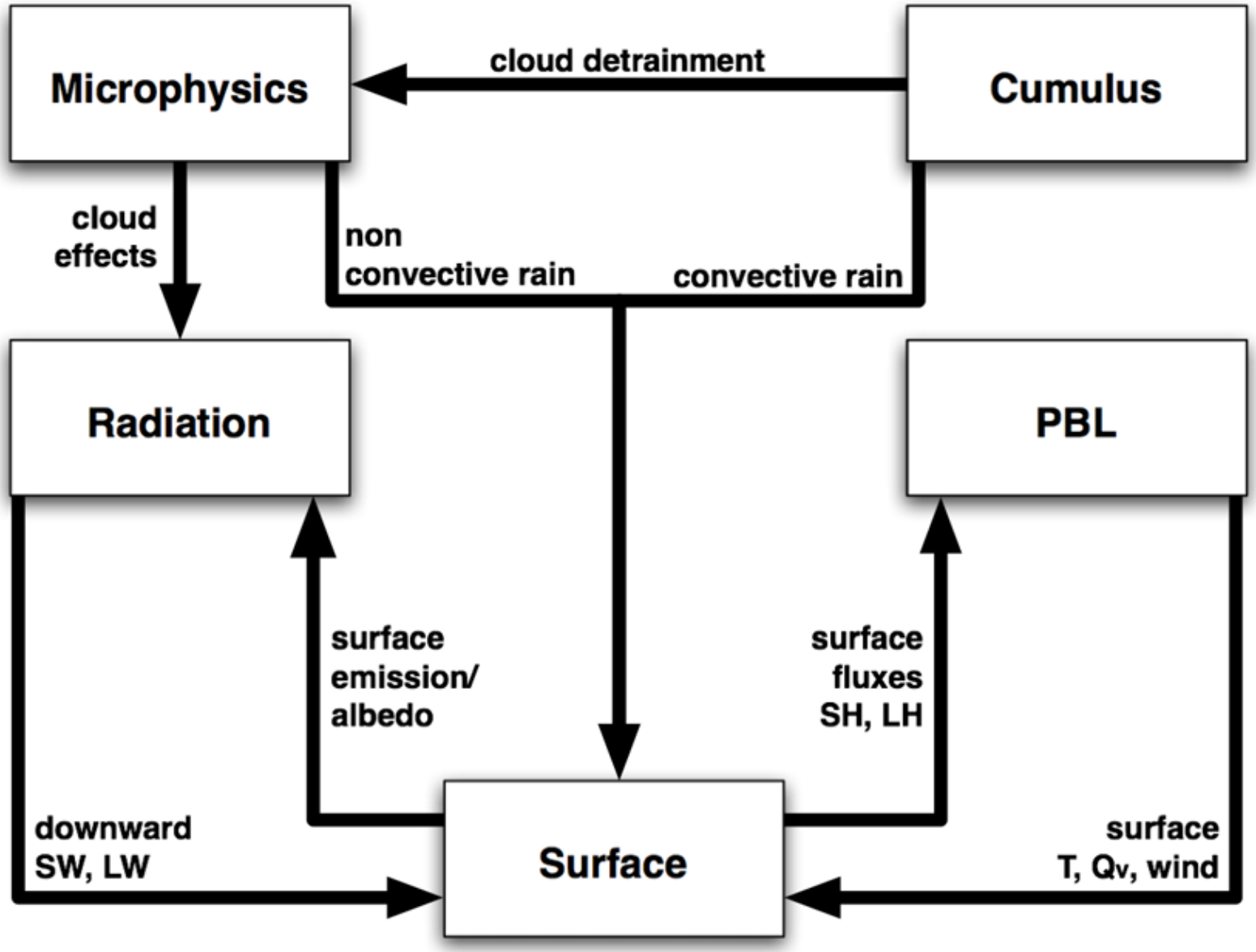
The software infrastructure



Static Geographical Data: land use, orography, water, urban areas...

Gridded Meteorological data: initial and boundary conditions from observations, reanalyses, ...

WRF physics (while the code run)



WRF physics - how many choices

- ✓ 18 **microphysics** schemes
- ✓ 10 **radiation** schemes
- ✓ 8 **land-surface** schemes
- ✓ 8 **surface layer** schemes
- ✓ 14 **PBL** schemes
- ✓ 3 **urban** schemes
- ✓ 16 **cumulus** schemes

But the pattern reduces substantially to some possibilities, due to internal dependency and kind of case study!

How does it really appear?

```
arch    compile    dyn_em    hydro          main       README      run    tools
chem    configure  external  inc            Makefile   README.md   share  var
clean   doc        frame     LICENSE.txt    phys       Registry    test   wrftladj
```

- ✓ **arch**: software architecture
- ✓ **chem**: chemistry package
- ✓ **clean, compile, configure**: executables for configuring WRF
- ✓ **doc**: useful documents
- ✓ **dyn_em**: dynamical core modules
- ✓ **main**: WRF main executables
- ✓ **phys**: physics parameterization modules
- ✓ **run**: where the simulation is run

The **run** folder

```
[andrea.zonato@hpc-head-n1 run]$ ls
aerosol.formatted                    CLM_ALB_ICE_DFS_DATA                ozone_lat.formatted
aerosol_lat.formatted                CLM_ALB_ICE_DRC_DATA                ozone_plev.formatted
aerosol_lon.formatted                CLM_ASM_ICE_DFS_DATA                README.namelist
aerosol_plev.formatted               CLM_ASM_ICE_DRC_DATA                README.physics_files
BROADBAND_CLOUD_GODDARD.bin          CLM_DRDSDT0_DATA                    README.rasm_diag
bulkdens.asc_s_0_03_0_9              CLM_EXT_ICE_DFS_DATA                README.tslist
bulkradii.asc_s_0_03_0_9             CLM_EXT_ICE_DRC_DATA                real.exe
CAM_ABS_DATA                         CLM_KAPPA_DATA                      RRTM_DATA
CAM_AEROPT_DATA                      CLM_TAU_DATA                        RRTM_DATA_DBL
CAMtr_volume_mixing_ratio.A1B        coeff_p.asc                         RRTMG_LW_DATA
CAMtr_volume_mixing_ratio.A2         coeff_q.asc                         RRTMG_LW_DATA_DBL
CAMtr_volume_mixing_ratio.RCP4.5     constants.asc                       RRTMG_SW_DATA
CAMtr_volume_mixing_ratio.RCP6       ETAMPNEW_DATA                       RRTMG_SW_DATA_DBL
CAMtr_volume_mixing_ratio.RCP8.5     ETAMPNEW_DATA_DBL                   SOILPARM.TBL
CAMtr_volume_mixing_ratio.SSP119     ETAMPNEW_DATA.expanded_rain_DBL     SOILPARM.TBL_Kishne_2017
CAMtr_volume_mixing_ratio.SSP126     GENPARM.TBL                         URBPARM_LCZ.TBL
CAMtr_volume_mixing_ratio.SSP245     HLC.TBL                             URBPARM.TBL
CAMtr_volume_mixing_ratio.SSP370     LANDUSE.TBL                         URBPARM_UZE.TBL
CAMtr_volume_mixing_ratio.SSP585     MPTABLE.TBL                         VEGPARM.TBL
capacity.asc                         namelist.input                      wrf.exe
CCN_ACTIVATE.BIN                     ozone.formatted
```

-Lookup Tables for various atmospheric coefficients

-Useful README files

- Exexutables for running the simulations

- Lookup Tables for landuse, soil and vegetation

- Table for setting up the simulation (time, domain, physics, ...)

The namelist.input

namelist.input

Introduction to WRF-URBAN

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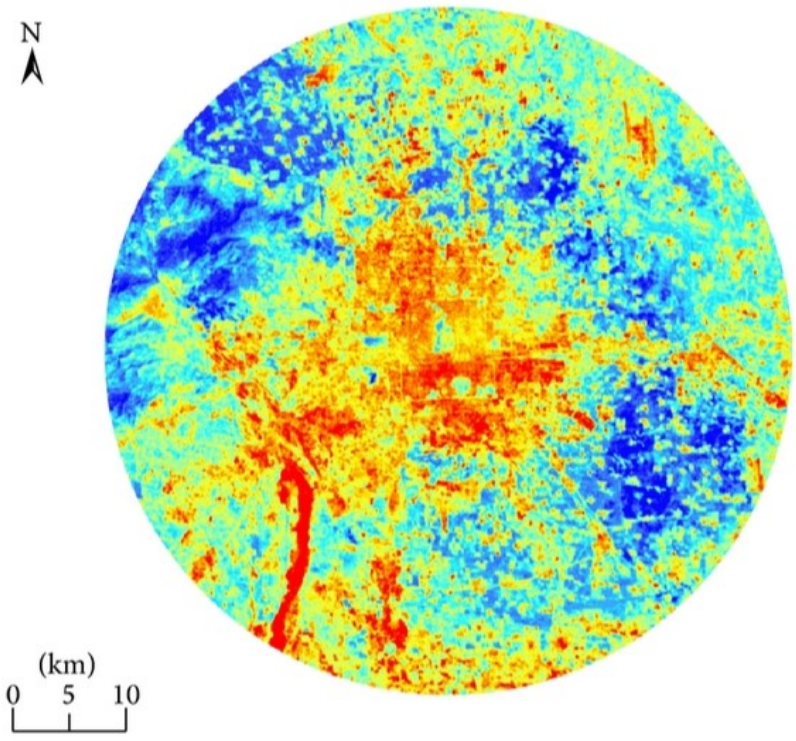

What is WRF-URBAN?

Tools/Parameterizations to account for urban areas in WRF

- ✓ Improve the reproduction of atmosphere processes within the cities
- ✓ Different land-atmosphere interaction **physical parameterizations**, called Urban Canopy Parameterizations (**UCP**)
- ✓ Different **urban morphology** methods
- ✓ **Cannot** resolve buildings and urban structures (**NOTE**: we are working at the **mesoscale!**)

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Operational:

- ✓ Estimate **impact of extreme events** on population thermal comfort
- ✓ Estimate **energy demand** for large urban areas
- ✓ Now-casting of extreme **air pollution events** (fires, dangerous releases, ...)

Research:

- ✓ Understand the relation between **urban climate and the surrounding environment** (land-sea breezes, complex terrain, storms, ...)
- ✓ Understand the effect of the city depending on its **geometrical/thermal features**
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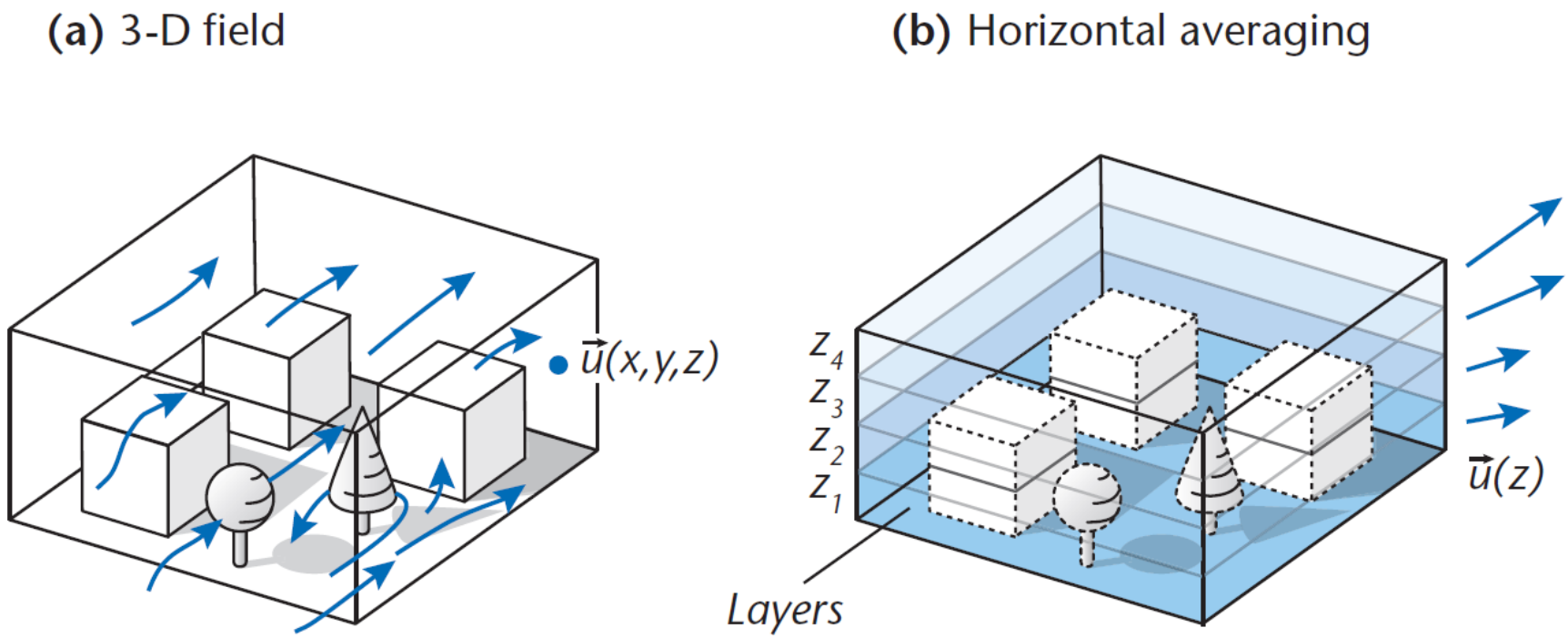
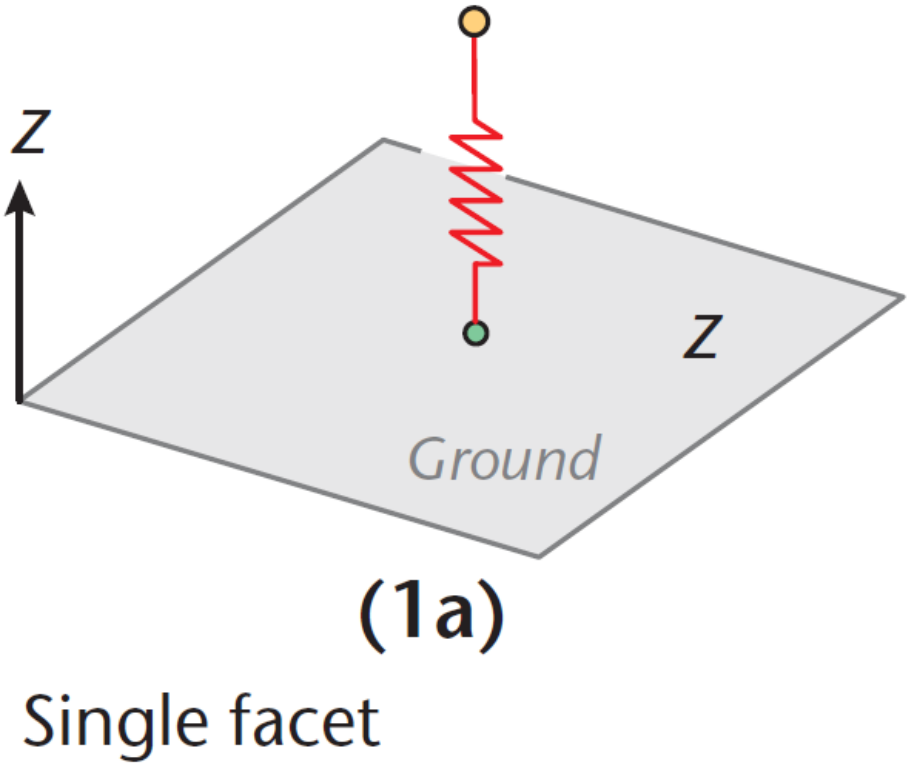
Why not building resolving?



Oke (2017)

UCPs in WRF:

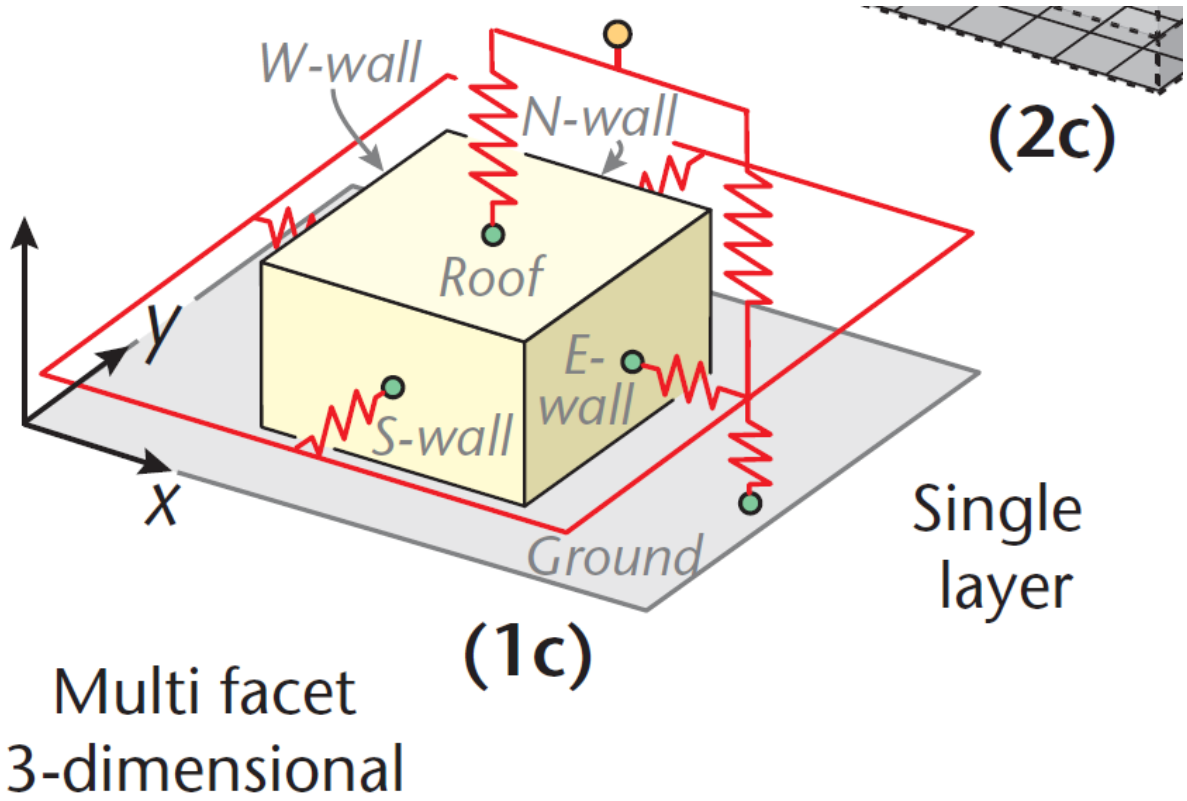
1) **BULK**: urban surfaces are flat and characterized by just land-use parameters (emissivity, roughness length, heat capacity,...)



Oke (2017)

UCPs in WRF:

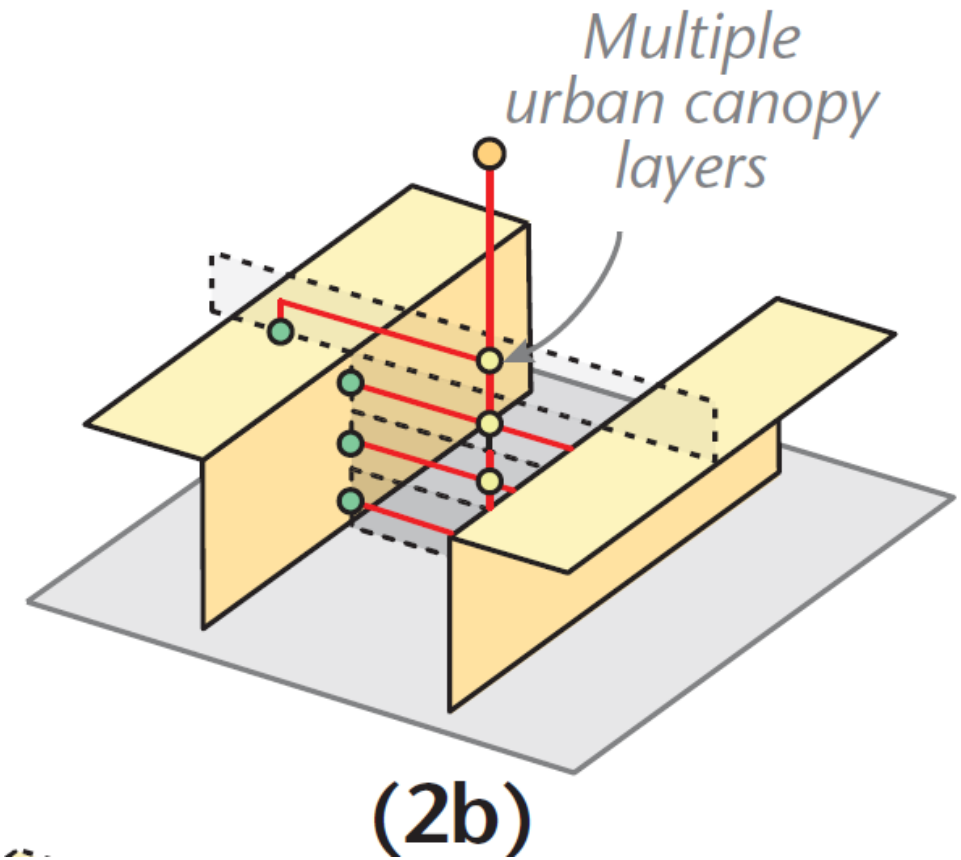
2) **Single Layer Urban Canopy Model (SLUCM)**, (Kusaka, 2000): urban heterogeneity is described by a single layer $\geq$ than the height of the highest buinding



Oke (2017)

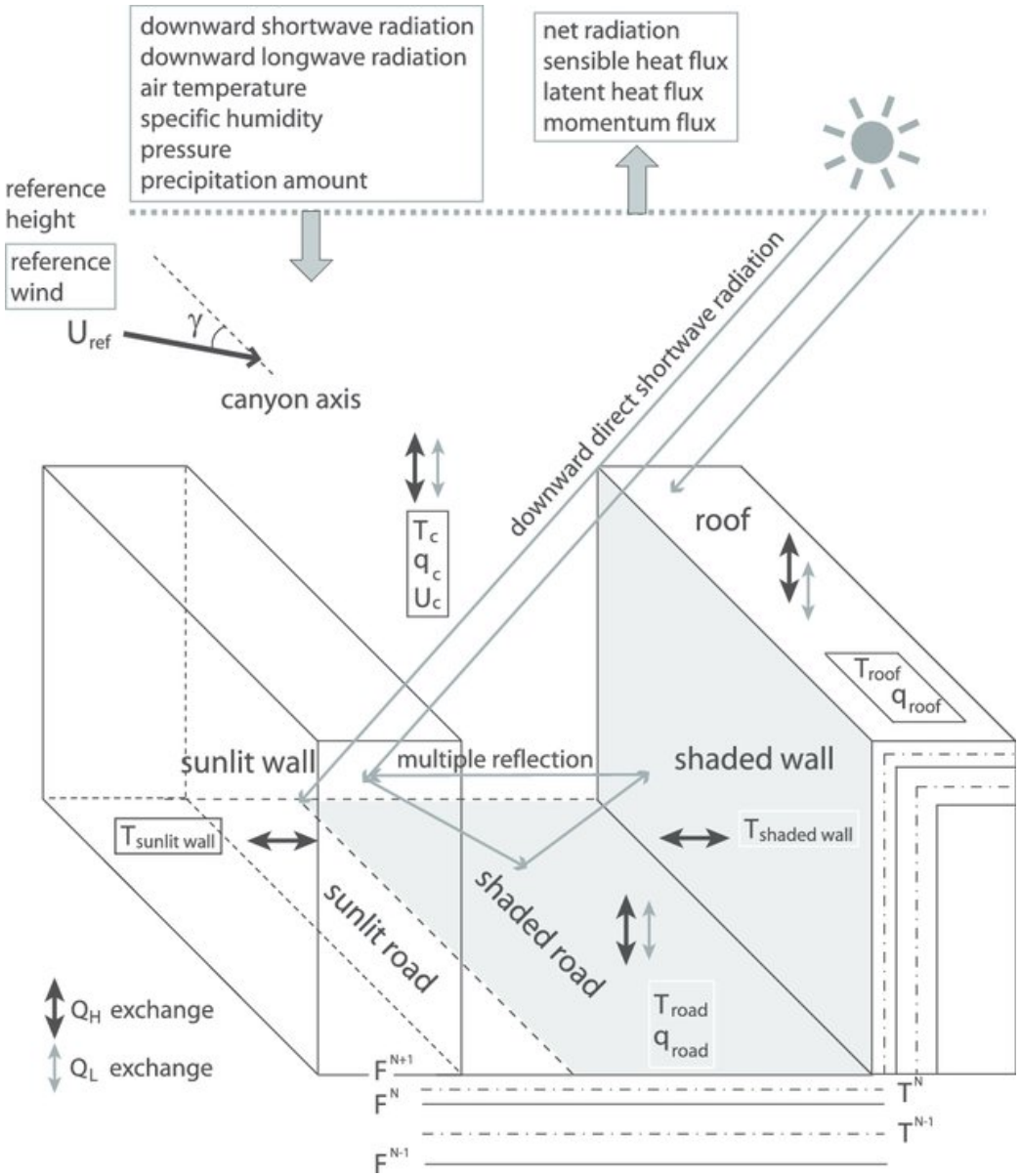
UCPs in WRF:

3) **Multi Layer Building Effect Parameterization (BEP)**, (Martilli, 2002): urban heterogeneity is described by sub-grid layers

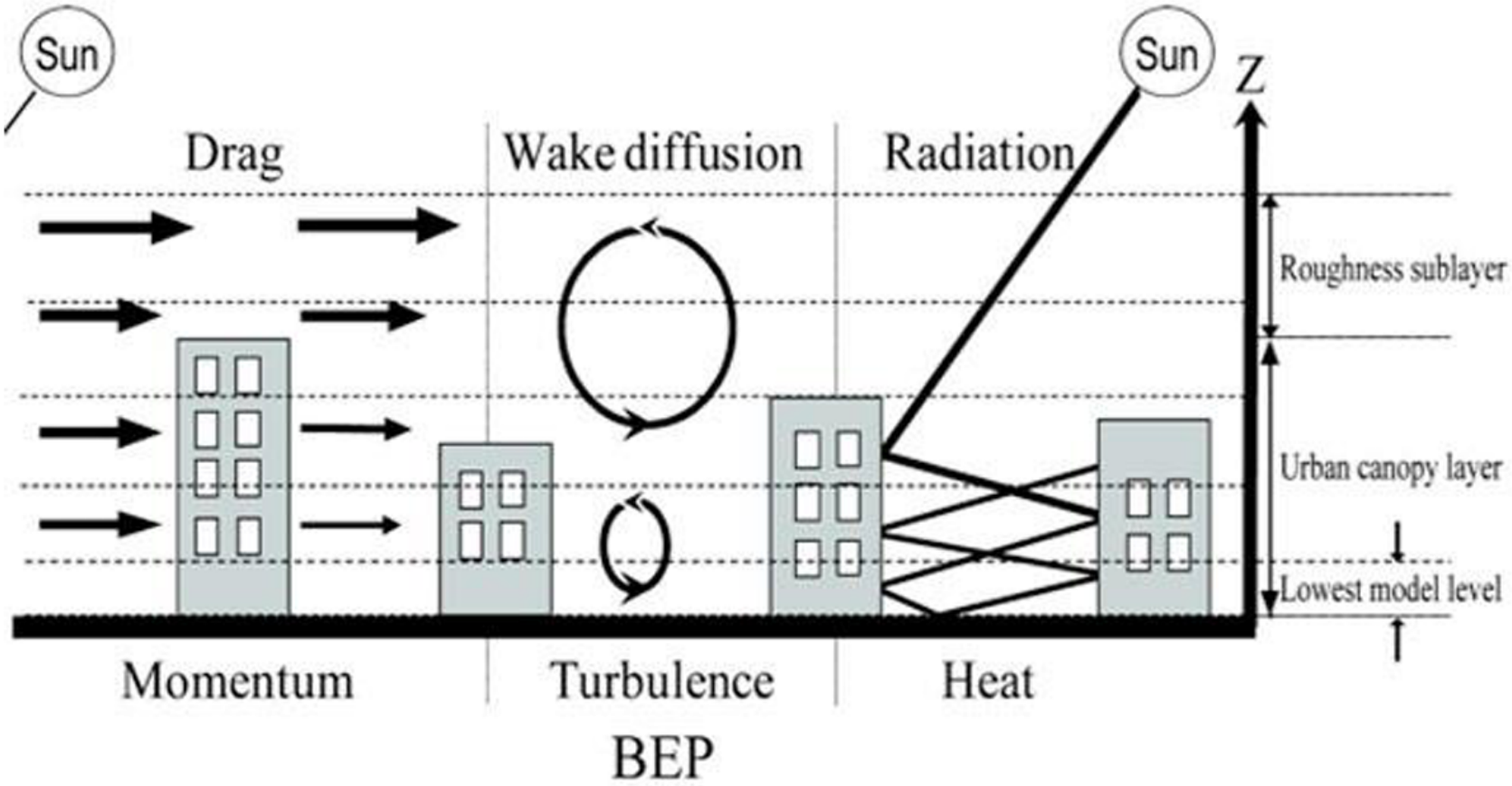


Oke (2017)

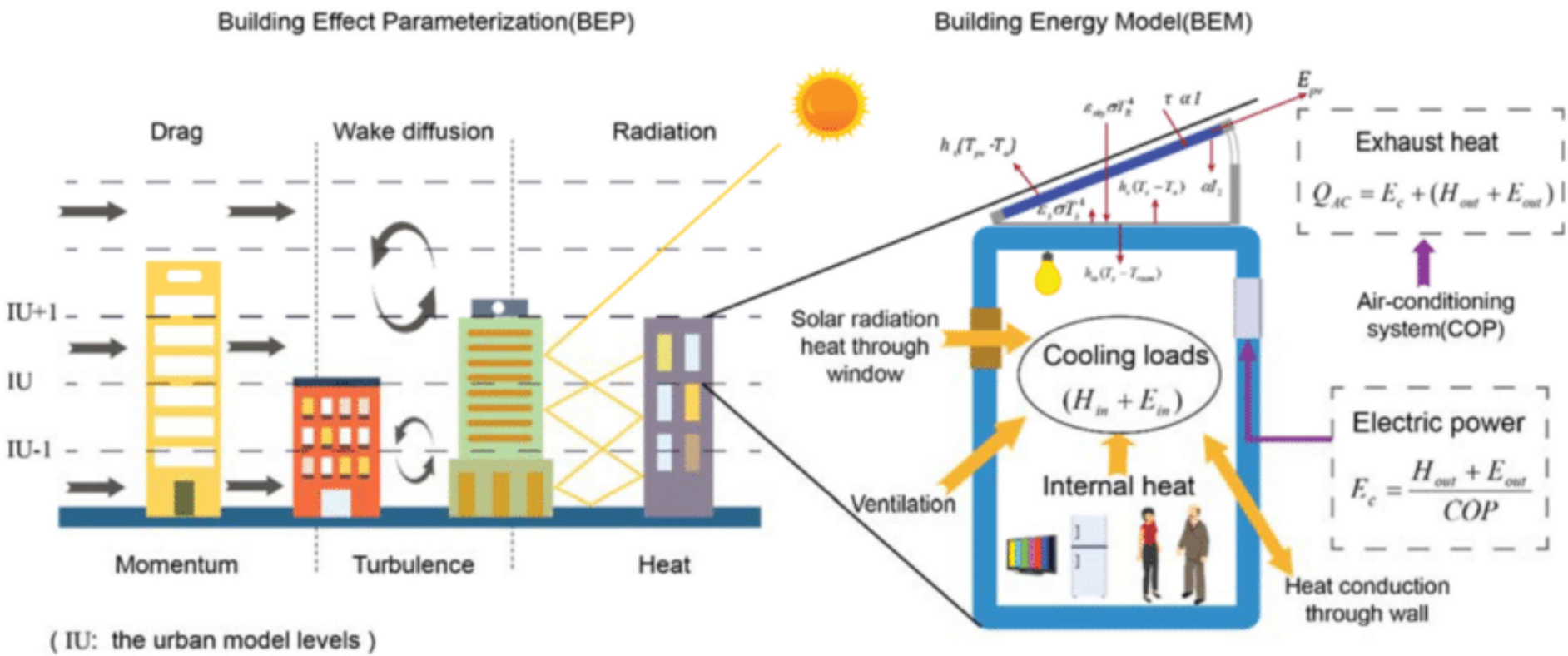
2) Single Layer Urban Canopy Model (SLUCM)



3) Building Effect Parameterization (BEP)



3.5) BEP+ Building Energy Model (BEM)



How to define the Urban Morphology in WRF?

Requisites:

- ✓ Should be suitable for building non-resolving UCPs
- ✓ Should describe the intra-variability within the city
- ✓ Should bring as much information as possible about urban geometries and thermal properties

What WRF have to offer?

- ✓ From Version 4.3 up to 11 different **urban classes (LCZ)** (3 before)
- ✓ **Look-up tables** to define relevant parameters for each class (URBPARM.TBL)
- ✓ **Input static fields** for ad-hoc definition of urban geometries

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Which variables are necessary?

1) BULK

- ✓ Urban areas extension through land use (urban/non-urban)

1) SLUCM and BEP+BEM

- ✓ Urban areas extension through land use (urban/non-urban)+ **urban classification into LCZ**
- ✓ Urban Fraction (Urban/Total for each cell)
- ✓ Mean building height and height distribution
- ✓ Plan area fraction
- ✓ Building Surface to Plan Area Ratio
- ✓ Look-up table for **building thermal properties**

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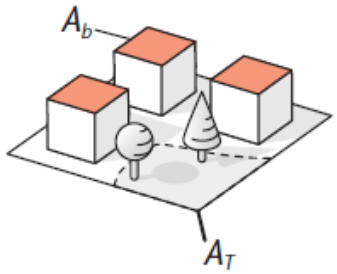
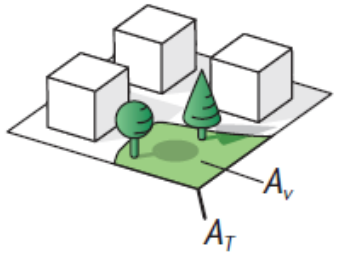
Urban geometrical properties

Urban cover

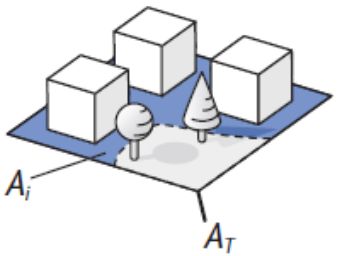
(a) $\lambda_b = A_b/A_T$



(b) $\lambda_v = A_v/A_T$

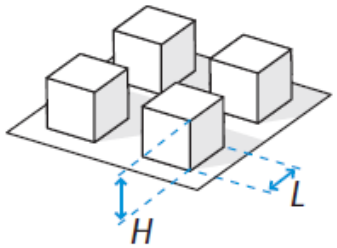


(c) $\lambda_i = A_i/A_T$

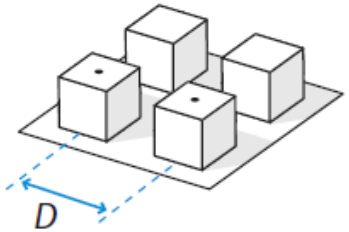


Length scales

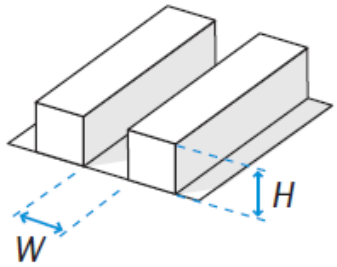
(d) Building dimensions



(e) Building spacing

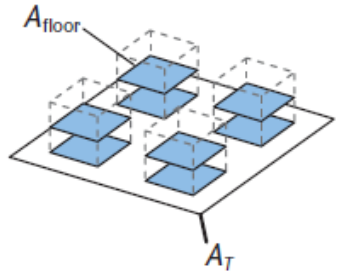


(f) $\lambda_s = H/W$

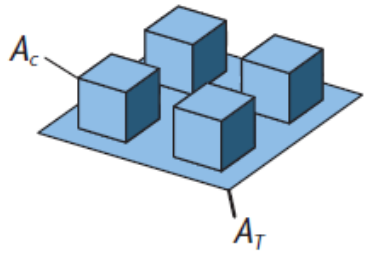


Urban structure

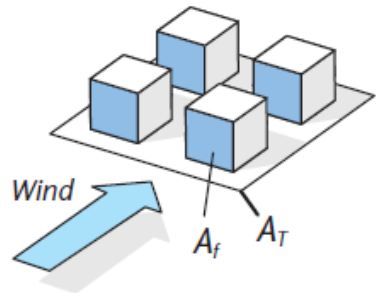
(g) $\lambda_{floor} = A_{floor}/A_T$



(h) $\lambda_c = A_c/A_T$



(i) $\lambda_f = A_f/A_T$



How in WRF? 1) Look-up Table

▸ URBPARM.TBL

How in WRF? 2)URB_PARAM static fields

▸ URB_PARAM

Available datasets

Digital Surface Models (In-situ measurements)

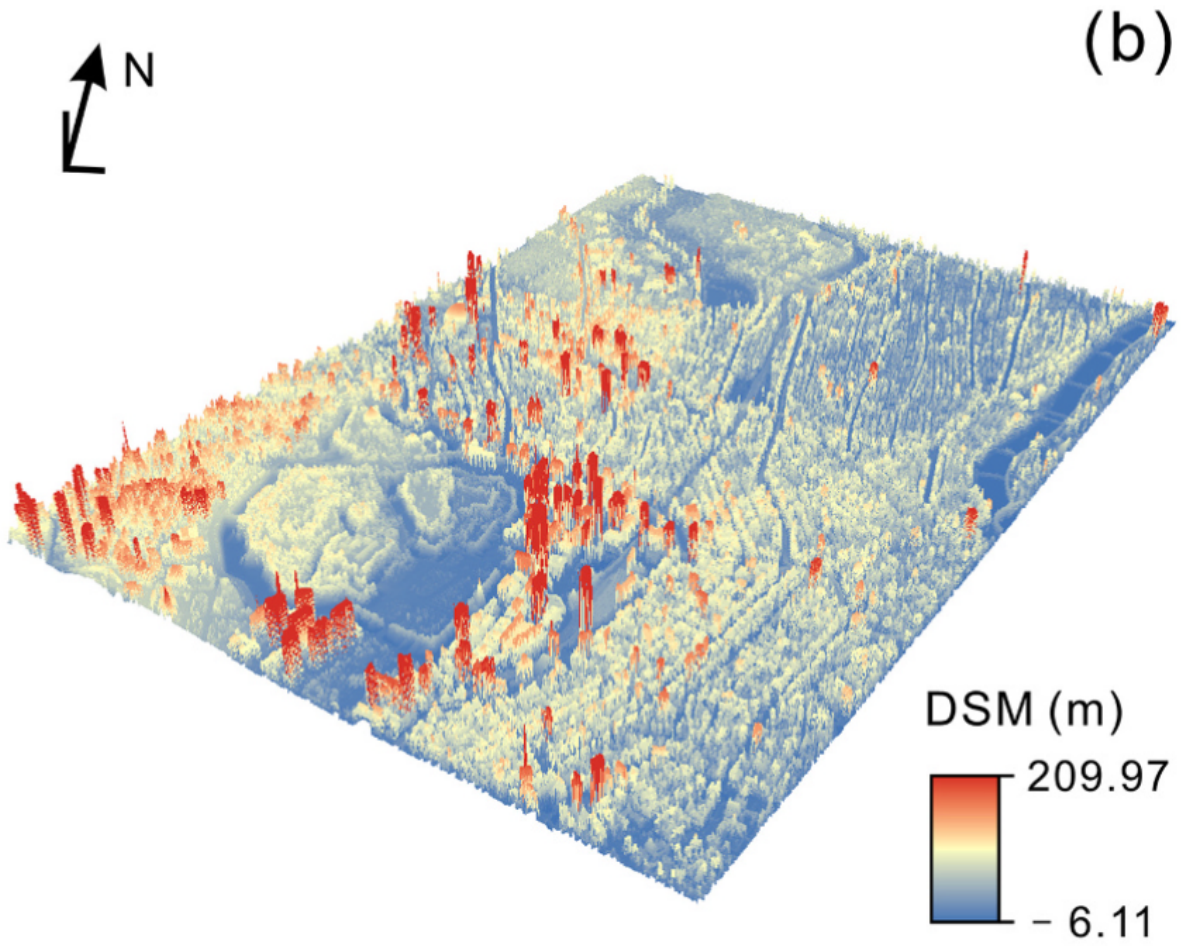
- ✓ Presents a reproduction of the real city from the real measurements
- × Data scarcity, ad-hoc data processing, not replicable

LCZ (or others) classification (from remote sensing)

- ✓ Replicable, potentially applicable for all the city of the world, in absence of other data
- × If not correctly calibrated, cannot represent consistently the urban morphology features

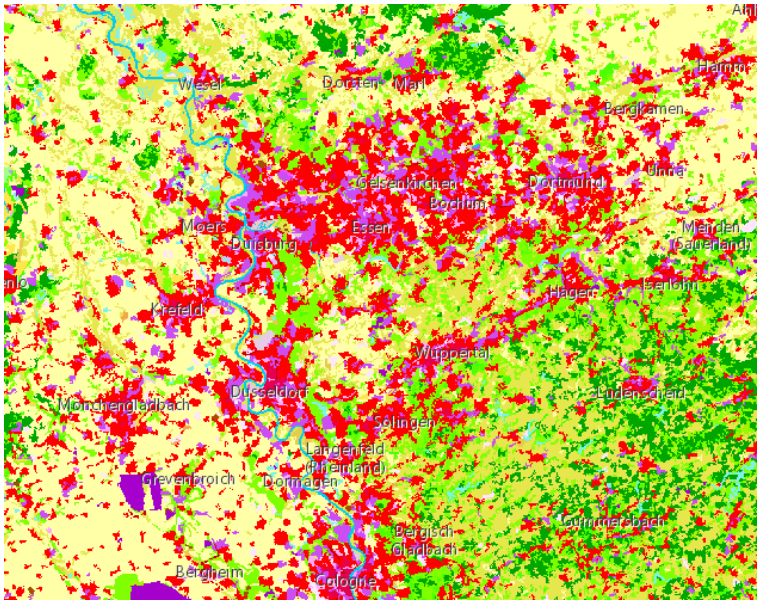
DSM (Digital Surface Models)

- **Unique** value for geometrical parameters
- **Categorical** value for thermal parameters

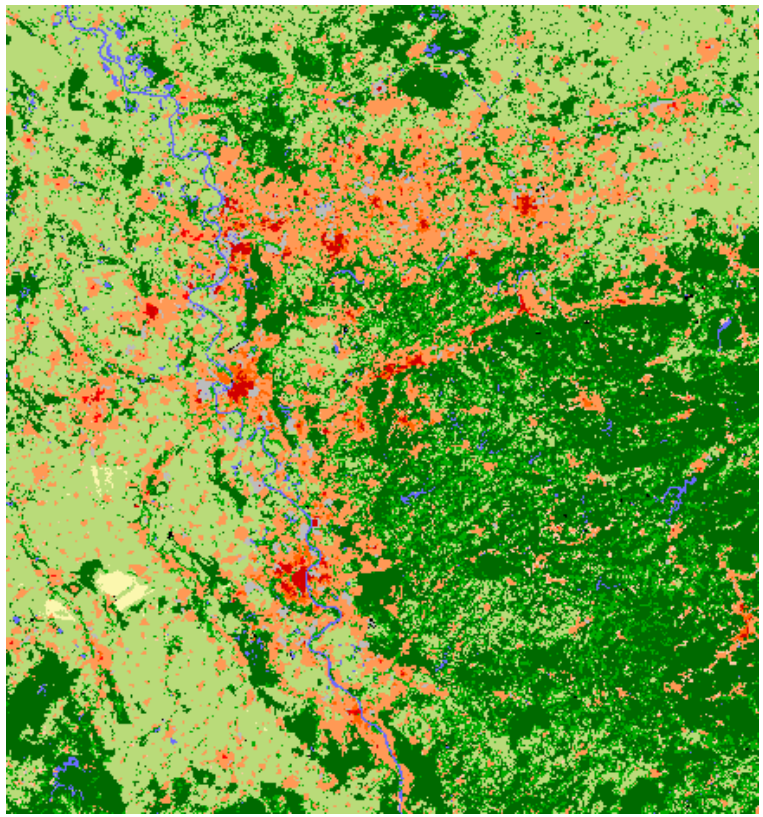


Remote sensing

- **Categorical** value for geometrical parameters
- **Categorical** value for thermal parameters

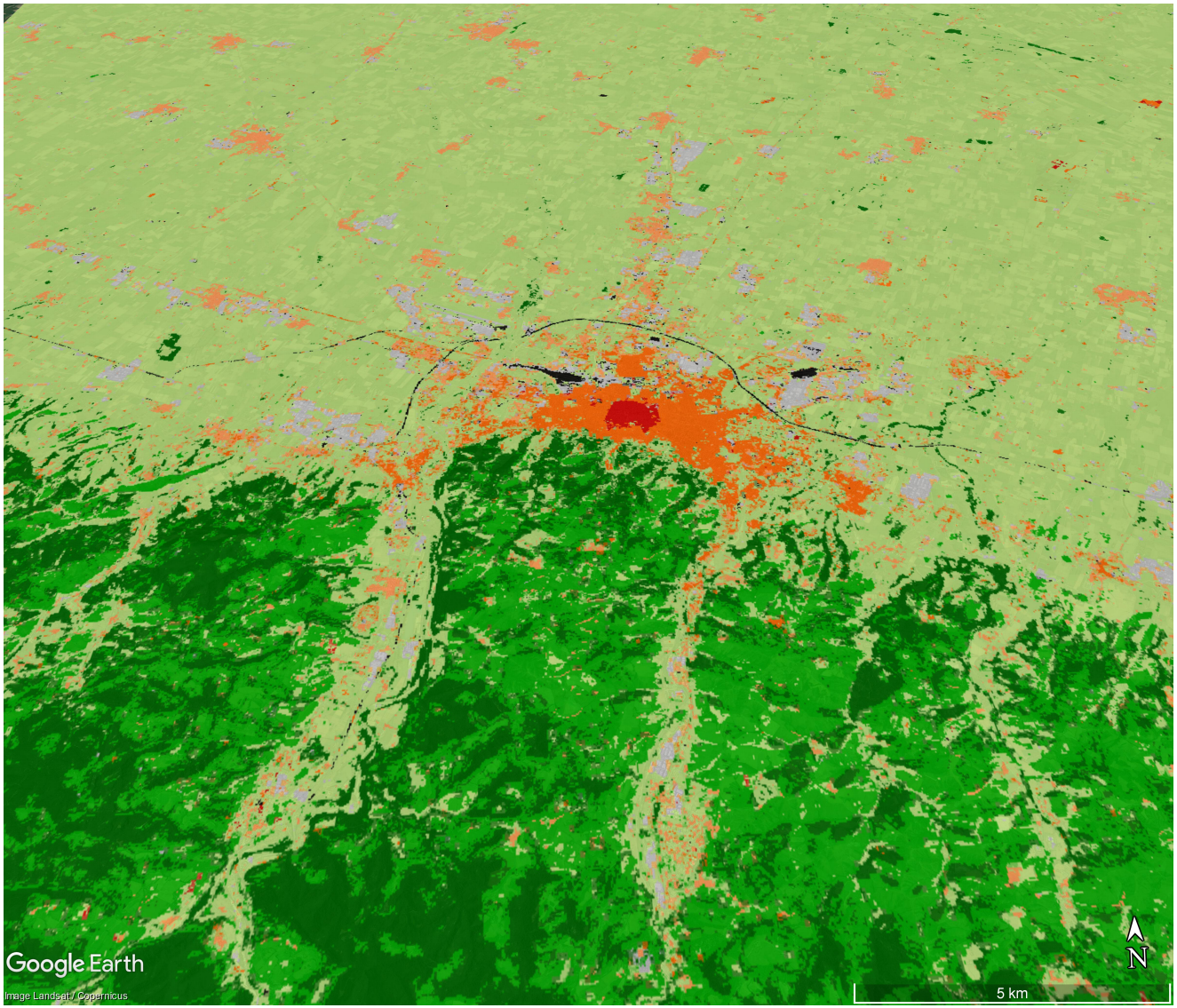


Corine 2018 (44 classes - 4 Urban)

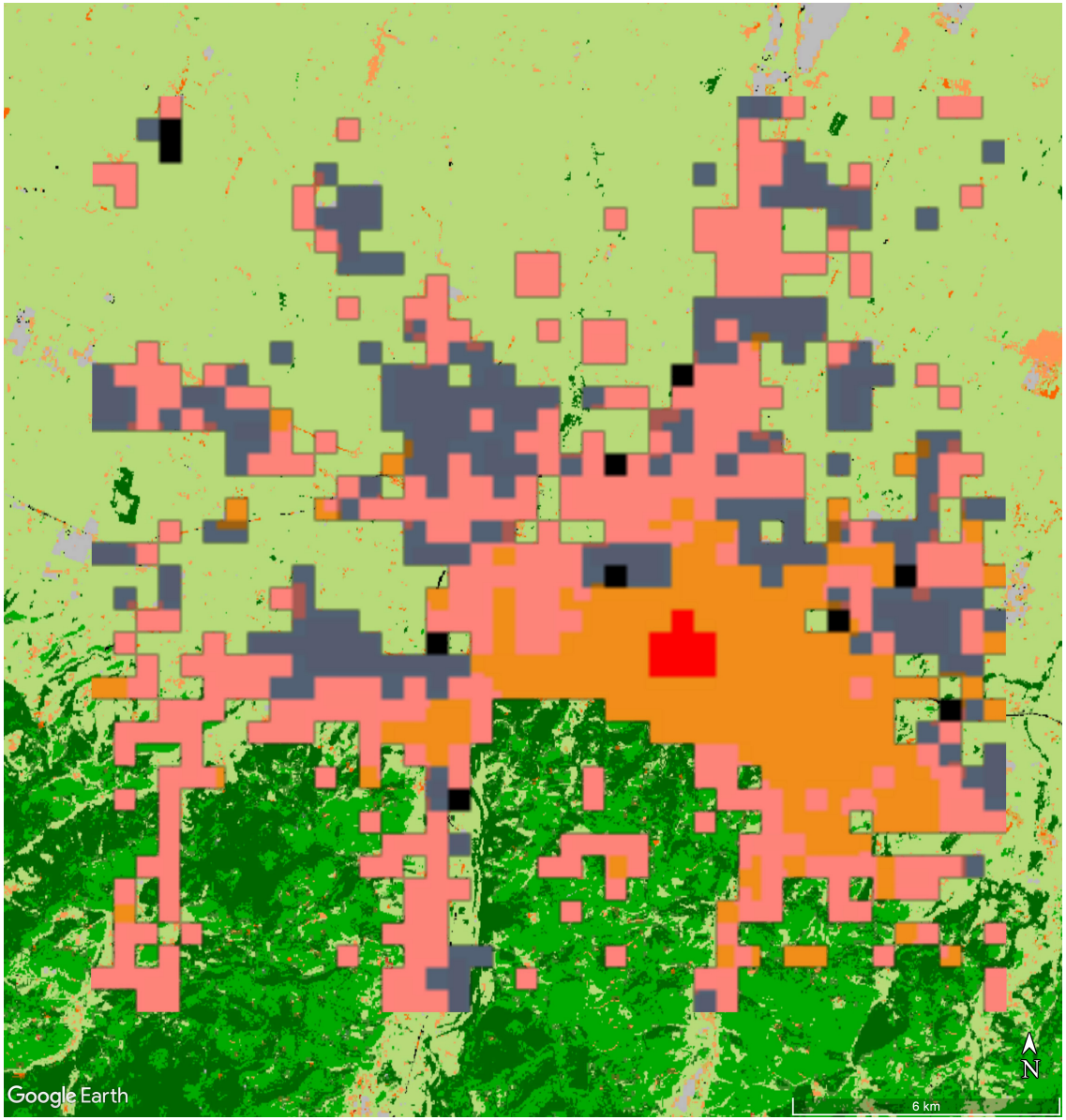


LCZ (17 classes - 10 Urban)

Bologna, LCZ, 30 m (Zonato et al., 2020)

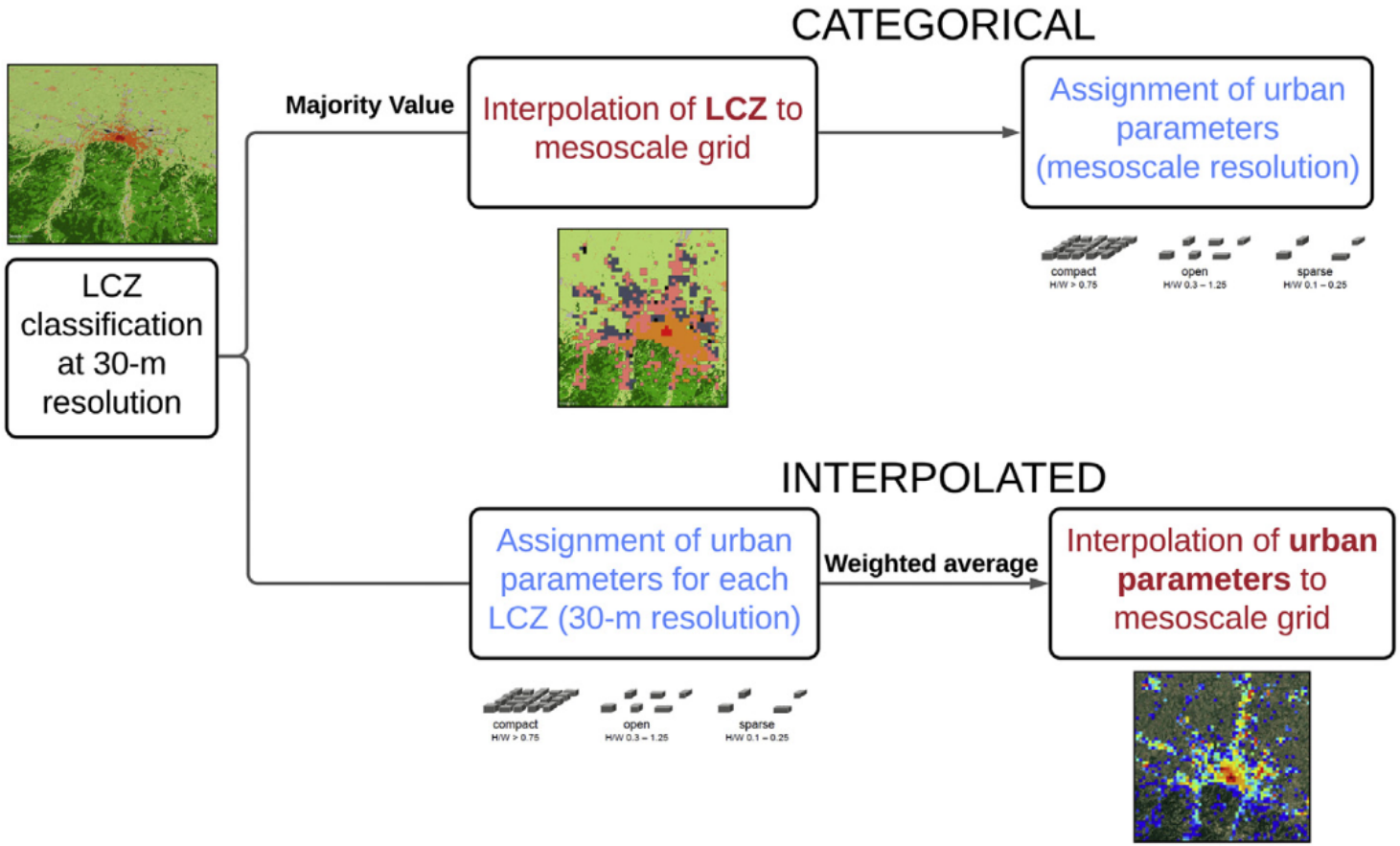


Bologna, LCZ, 500 m (Zonato et al., 2020)

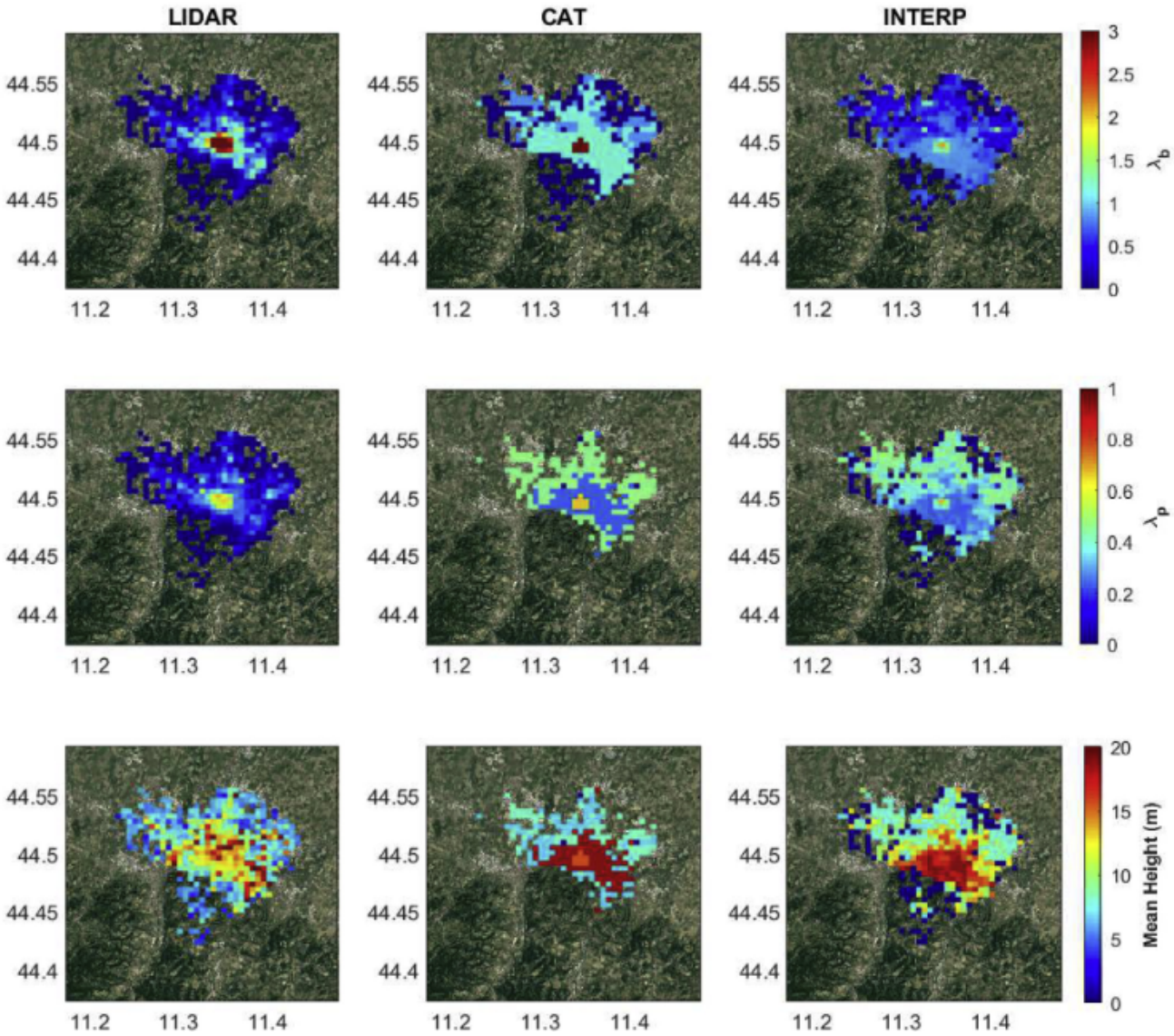


Interpolation of LCZ (Zonato et al., 2020)

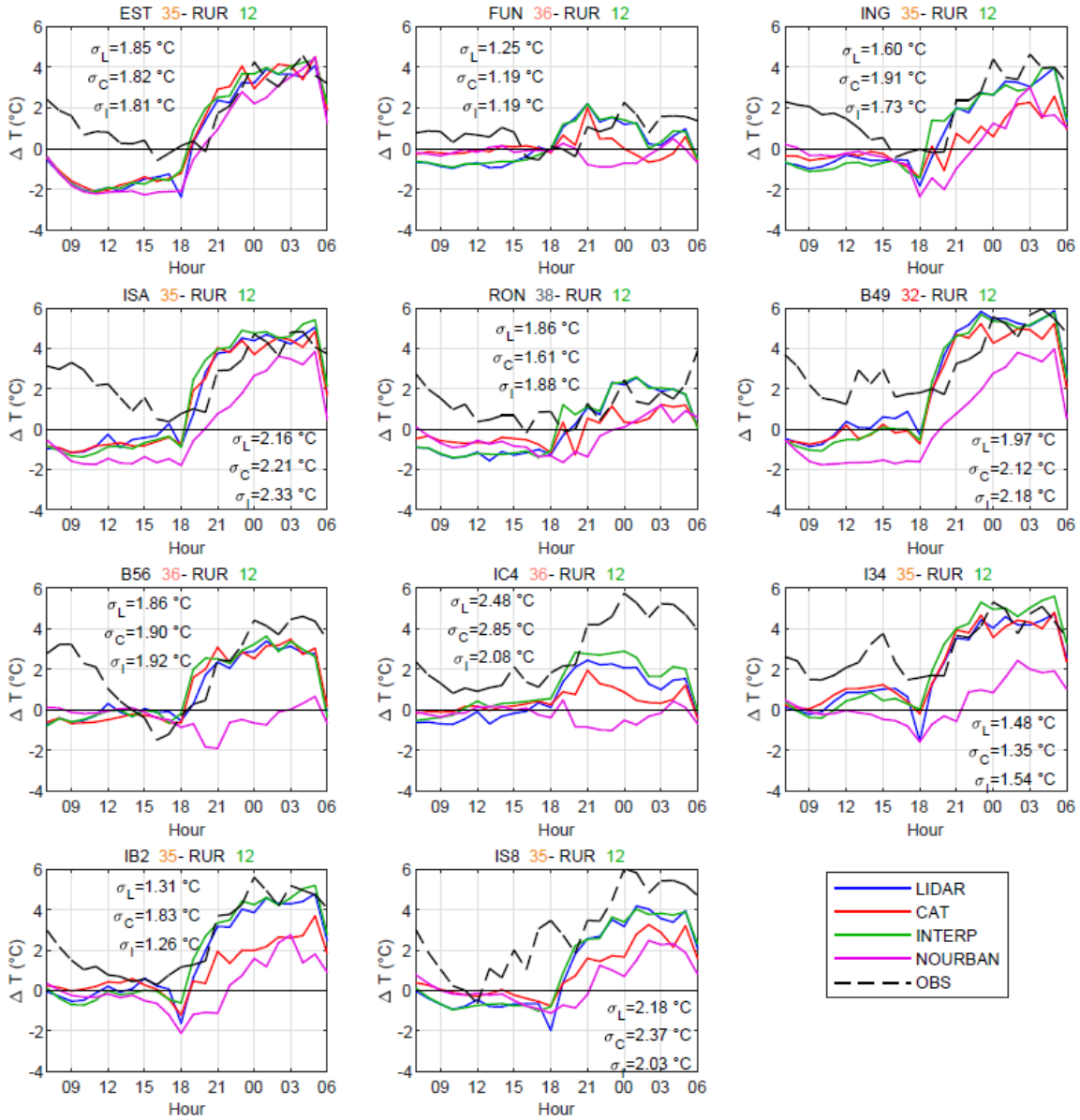
- **Unique** value for geometrical parameters
- **Categorical** value for thermal parameters



Comparison of the three methods - morphology



Comparison of the 3 methods - 2m air temperature

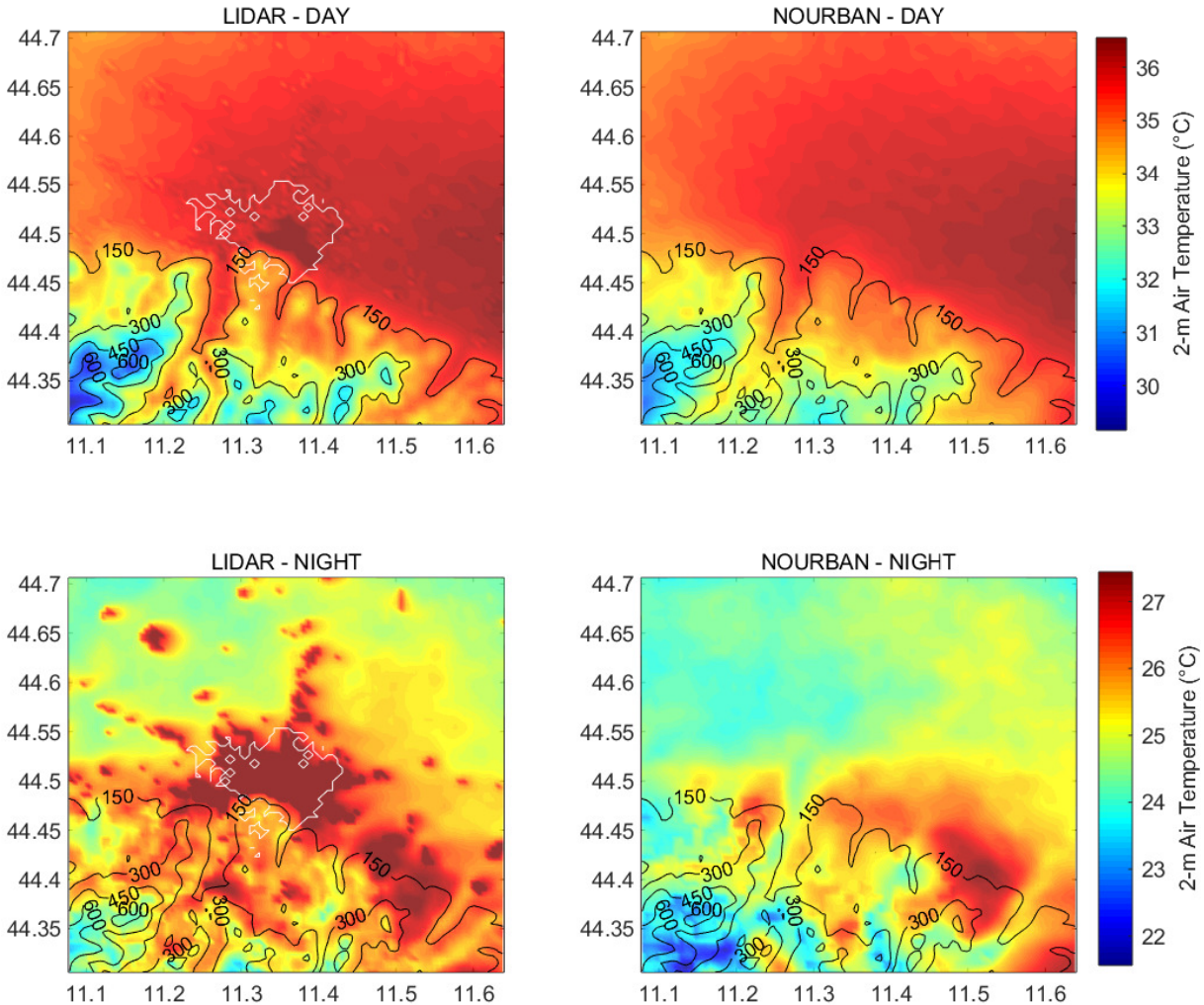


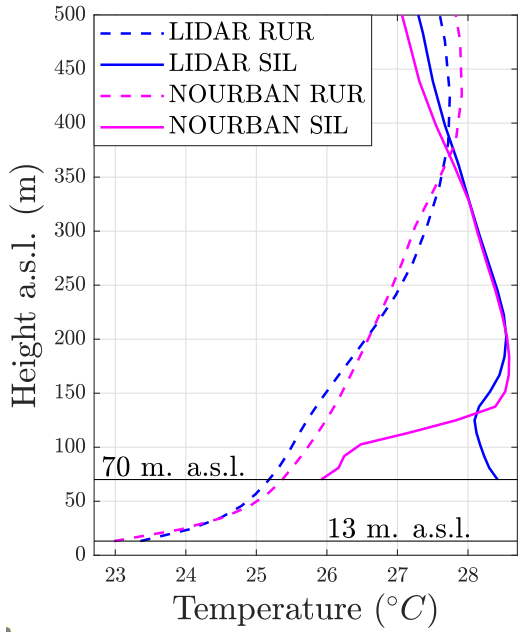
Applications

What do these tools allow us to do?

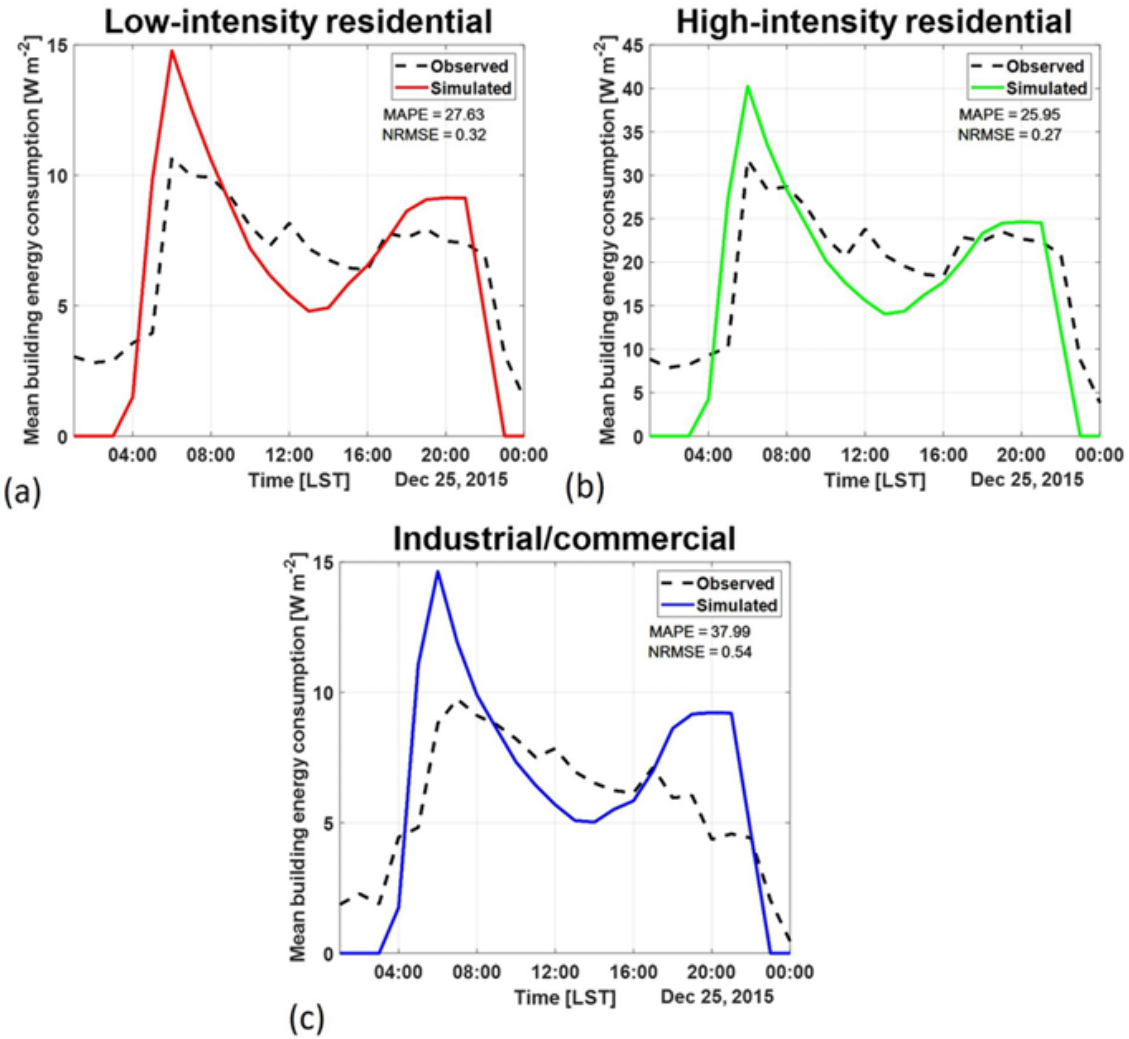
- ✓ Estimation of the 3D structure of the Urban Heat Island vs no-urban conditions
- ✓ Estimation of energy consumption by buildings
- ✓ Evaluation of urban climate for climate change/urban expansion/ heat waves
- ✓ **Estimation of the effect of mitigation strategies**

3D structure of UHI (Zonato et al.,2020)

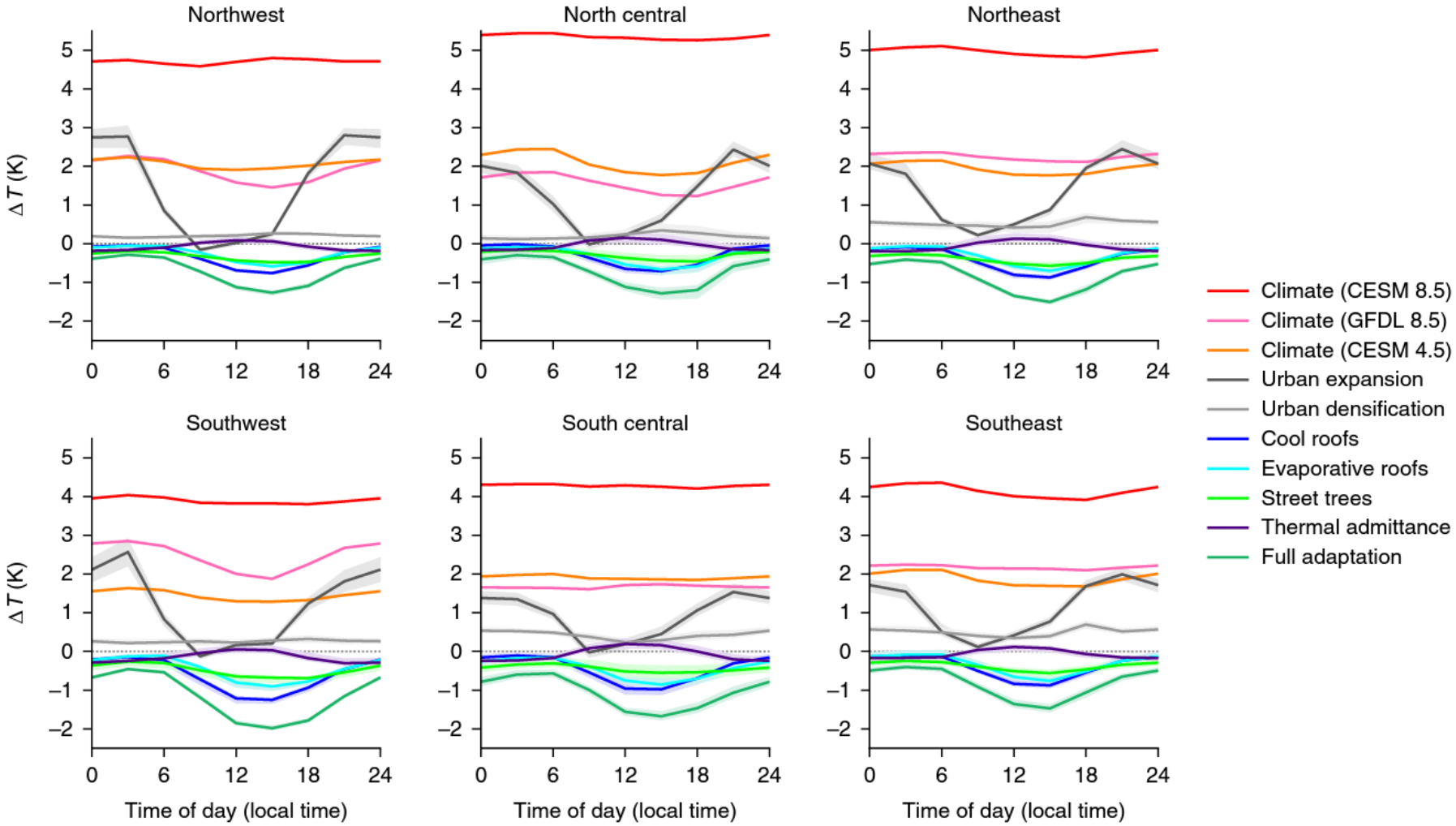




Estimation of buildings EC (Pappaccogli et al., 2021)



Estimation of CC scenarios (Krayenhoff et al.,2018)



Effect of (rooftop) mitigation strategies (Zonato, 2022)

Since WRF 4.3 (May 2021), WRF-Urban has:

- ✓ An updated coefficient for building-induced drag
- ✓ An extension of urban classes from 3 to 11
- ✓ A parameterization that accounts for the permeability of urban materials
- ✓ A new multi-layer parameterization for **green roofs** (GR)
- ✓ A new single-layer parameterization for **Photovoltaic panels** (PVP)

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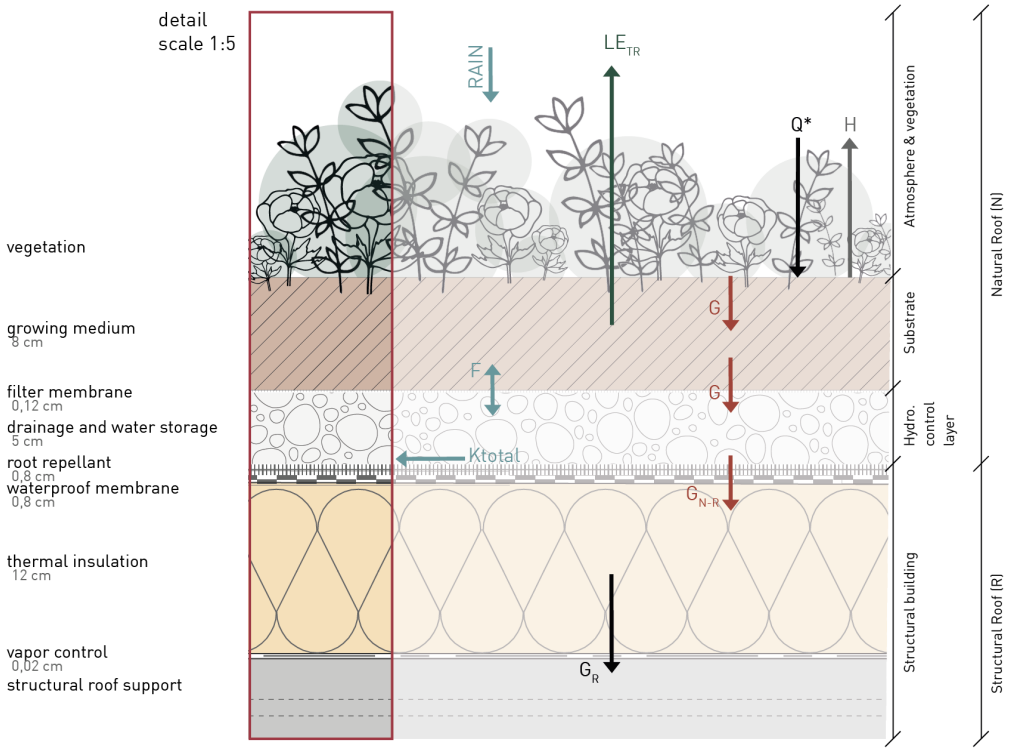
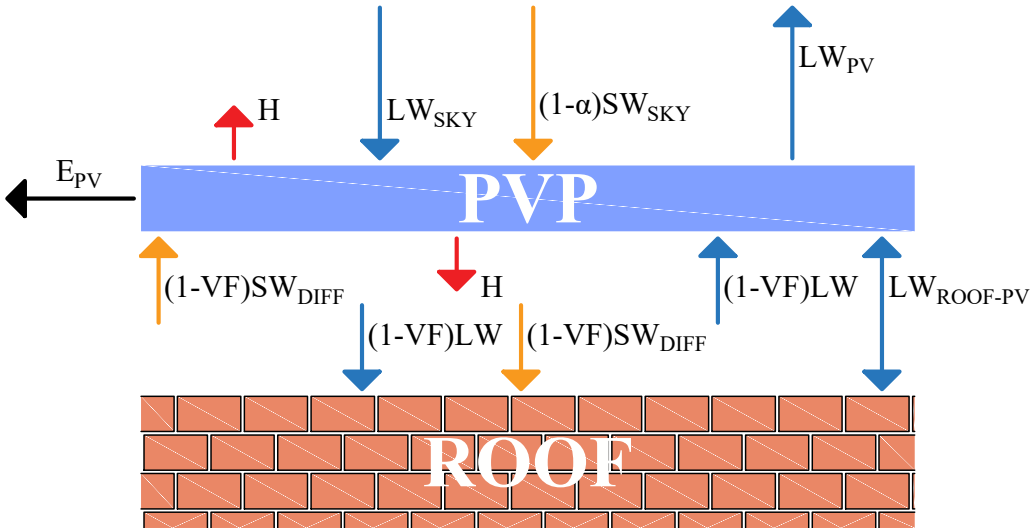
The GR parametrization - (de Munck et al., 2013)



- 10 layers (5 substrate - 5 structural building)
- Sensible/Latent heat exchange between layers and atmosphere (similar to Noah-NoahMP)
- Thermal coefficients humidity-dependent
- Irrigation through precipitation in the GR first layer

The PVP parametrization (Jones et al., 2002)

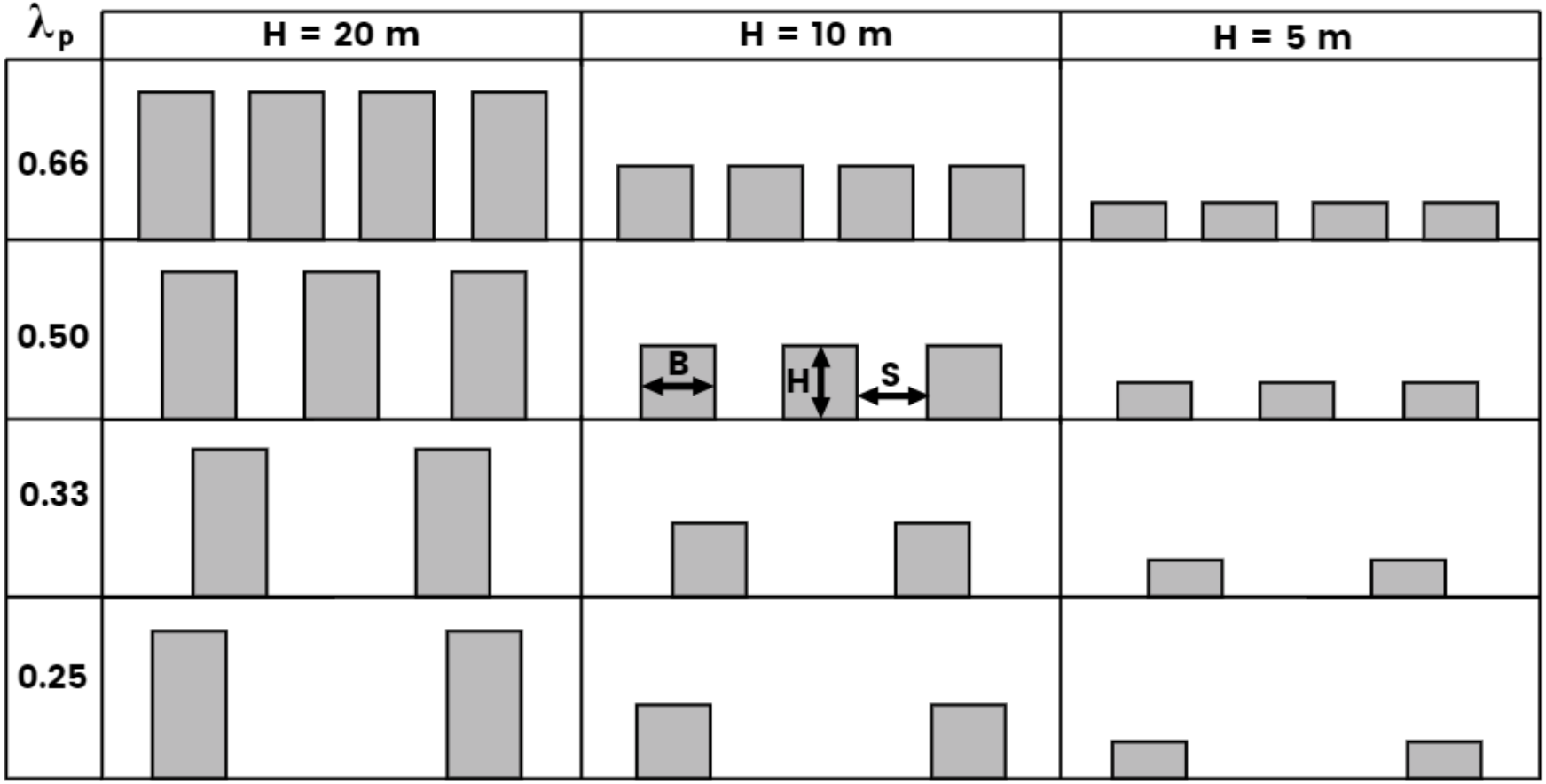
- PVP // roof
- single layer
- T_{PV} explicitly calculated



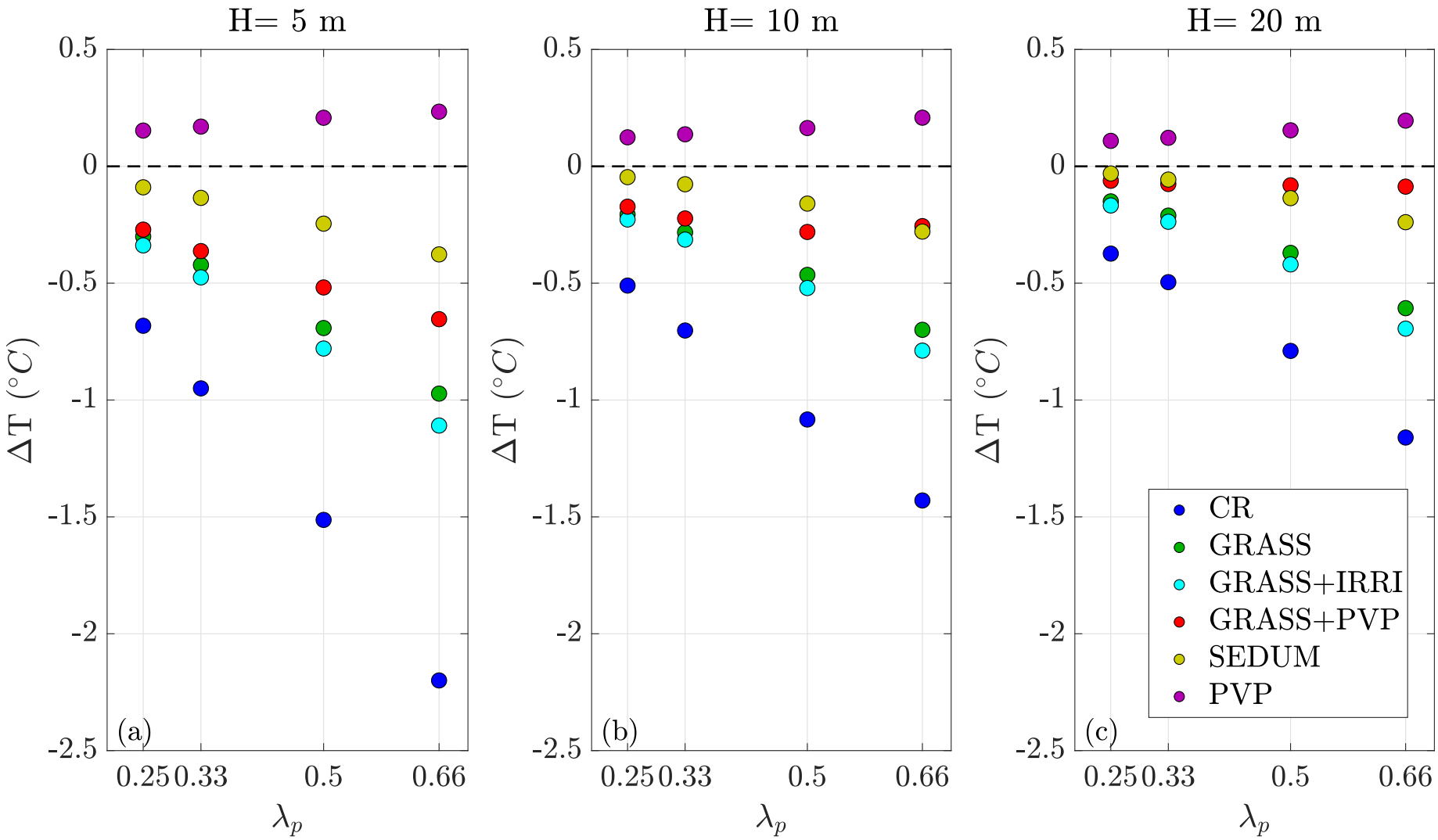
Heat balance equation for RPVP

$$
\begin{aligned}
C_{\text{module}} \frac{\partial T_{PV}}{\partial t} = & \left(1-\alpha_{PV}\right) SW^{\downarrow}_{\text{sky}} + \varepsilon^{U}_{PV} LW^{\downarrow}_{\text{sky}} - LW^{\uparrow}_{PV} + LW^{\updownarrow}_{roof-PV} \\
& -E_{PV} - H^{\uparrow} - H^{\downarrow} \\
& +(1-\text{VF}) \left[\left(1-\alpha_{PV}\right) SW_{\text{DIFF}} + LW^{\downarrow}_{\text{sky}}\right]
\end{aligned}
$$

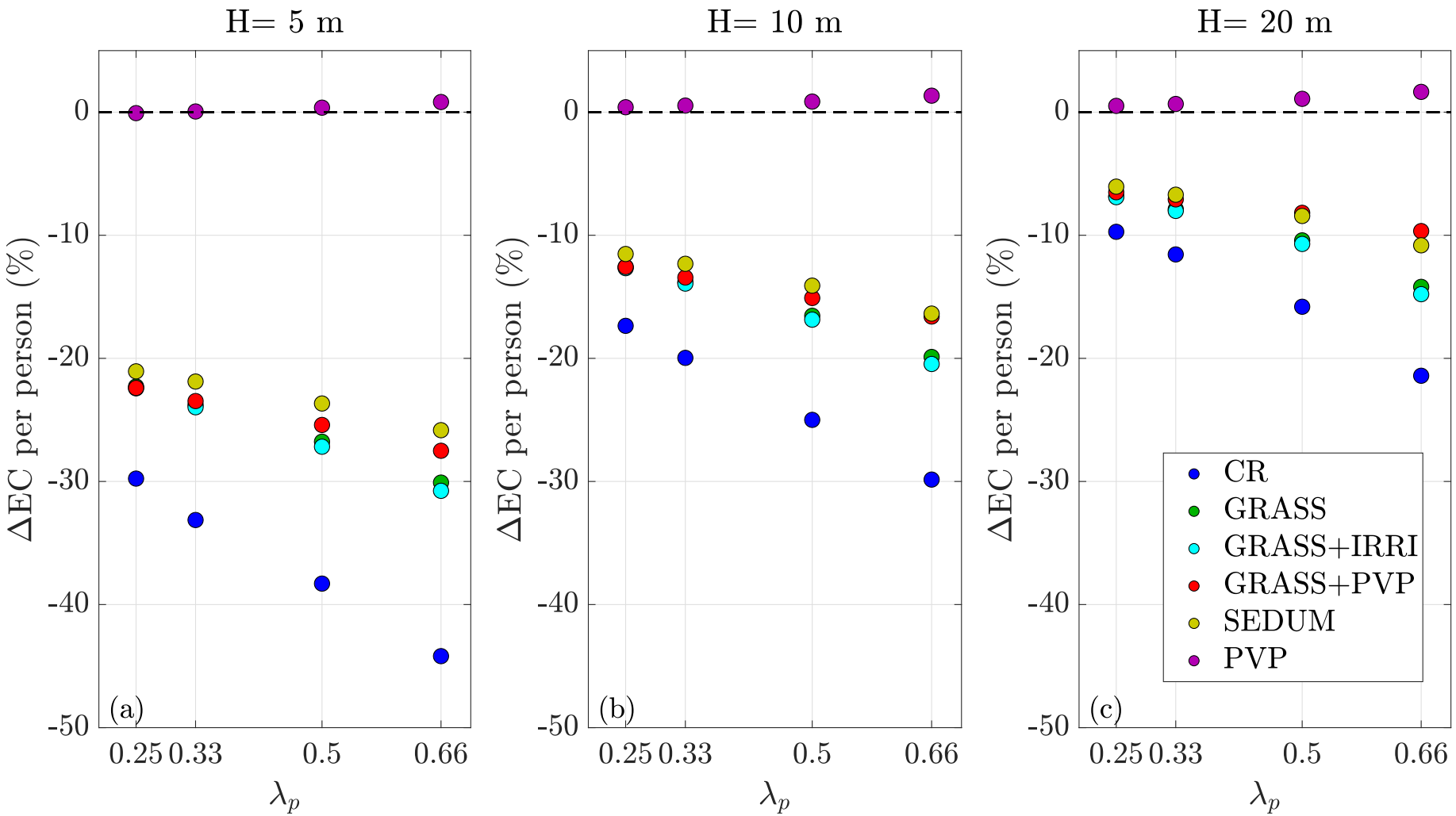
Results - Urban configurations



Effect on 2-m air temperature - Summer



Effect on energy consumption - Summer



Thank you for the attention,

and see you at the WRF exercises!

... Questions?