Land surface-atmosphere interactions simulated by the ICON atmospheric model

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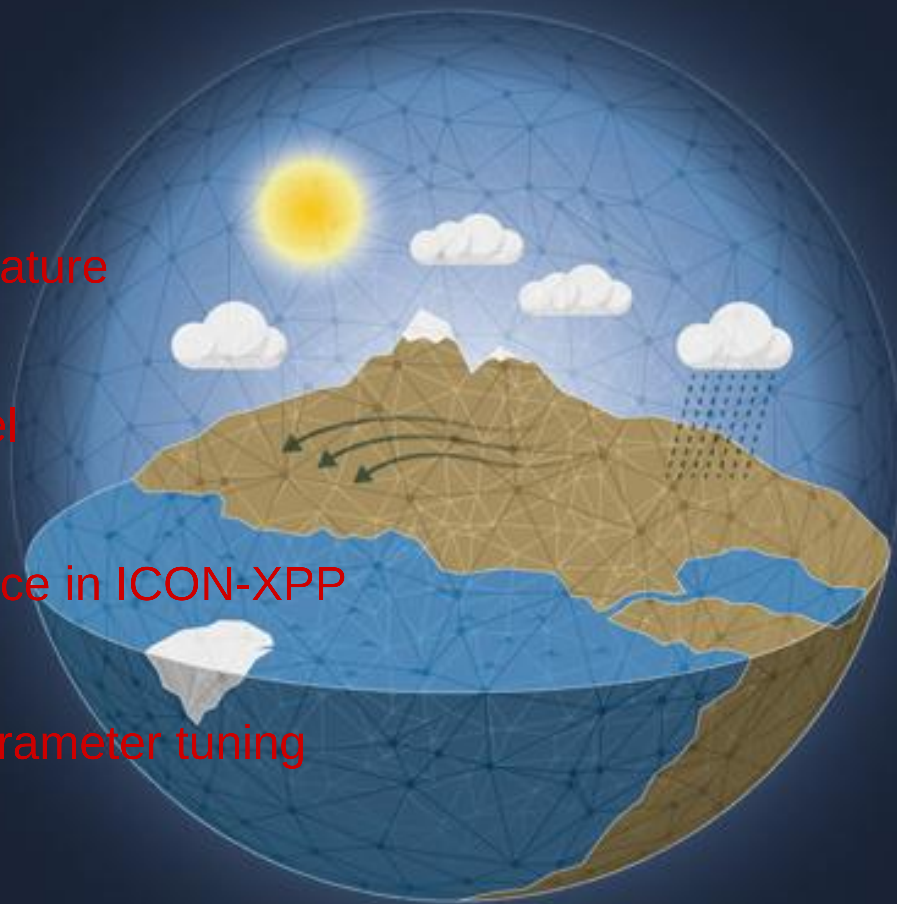
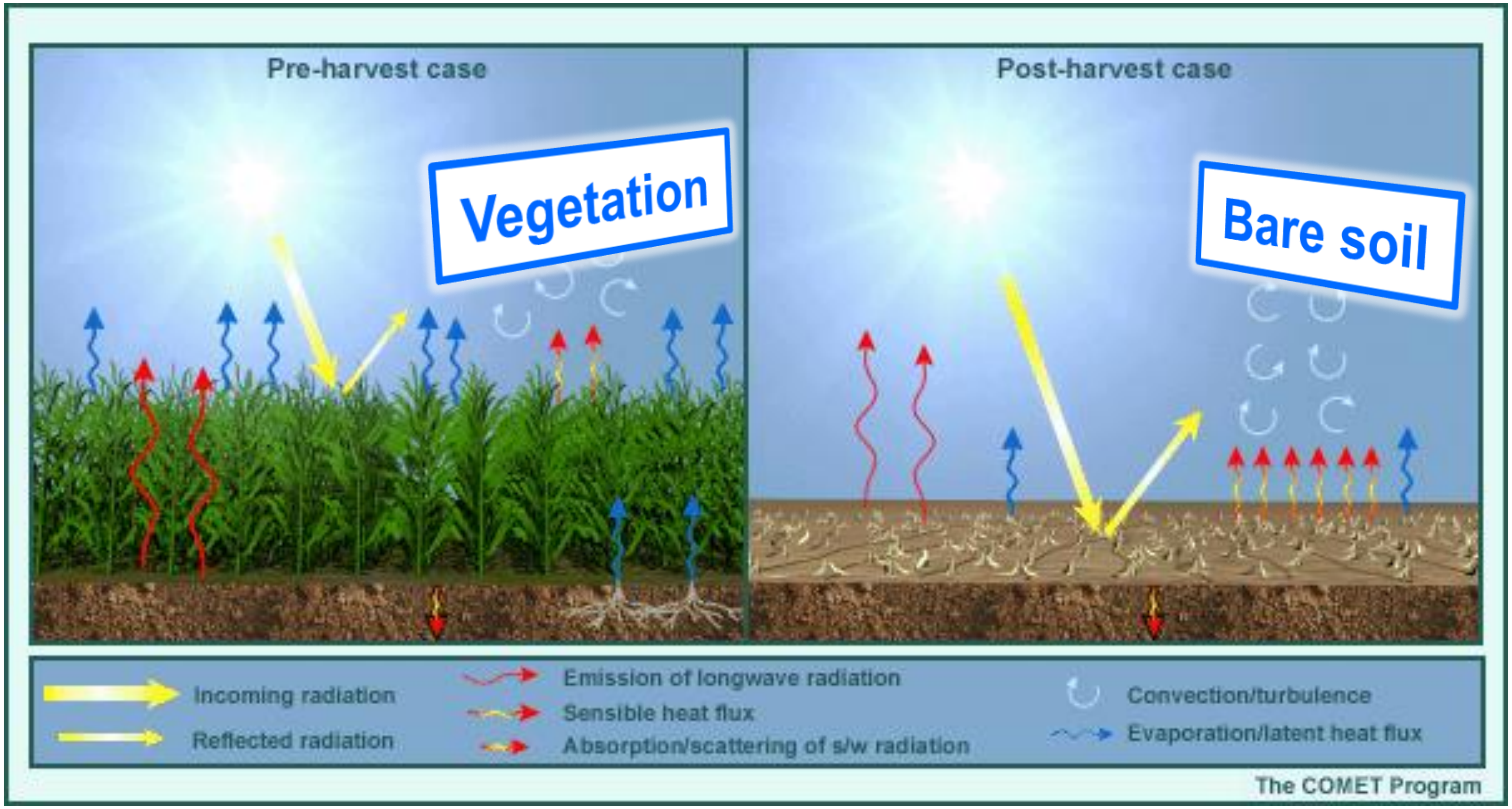
Workshop on surface process coupling and its interactions with the atmosphere, 9-10 Apr. 2025, Bonn, Germany

Outline

- Skin temperature
- Urban model
- Water balance in ICON-XPP
- Adaptive parameter tuning



What is the surface temperature in TERRA?



The problem …

- The amplitude of the diurnal cycle of the surface temperature in TERRA was systematically underestimated.
- The amplitudes of the diurnal cycles of the soil temperatures in TERRA were systematically overestimated.
- In TERRA, there was no representation of the vegetation in the surface energy balance. This means, there was no energy budget including a temperature for the vegetation layer (canopy temperature missing).
- The insulating effects by the vegetation at the sub-canopy level were missing.
- Including these two effects in TERRA can improve the simulation of surface and of soil temperatures (see e.g. Deardorff 1978, Schulz et al. 1998, or Vogel et al. 2015).

Surface temperature in TERRA

(Schulz et al. 2016)

$$C_s \frac{\partial T_s}{\partial t} = R_{SW} + R_{LW} + LE + H + G$$

T_s : surface temperature
C_s, t : heat capacity per unit area, time
R_{SW}, R_{LW} : net shortwave radiation flux, net longwave radiation flux
LE, H, G : latent heat flux, sensible heat flux, ground heat flux

Schulz, J.-P., G. Vogel, C. Becker, S. Kothe, U. Rummel and B. Ahrens, 2016: Evaluation of the ground heat flux simulated by a multi-layer land surface scheme using high-quality observations at grass land and bare soil, *Meteor. Z.*, **25**, 607-620.

Skin temperature in IFS

(Viterbo and Beljaars 1995)

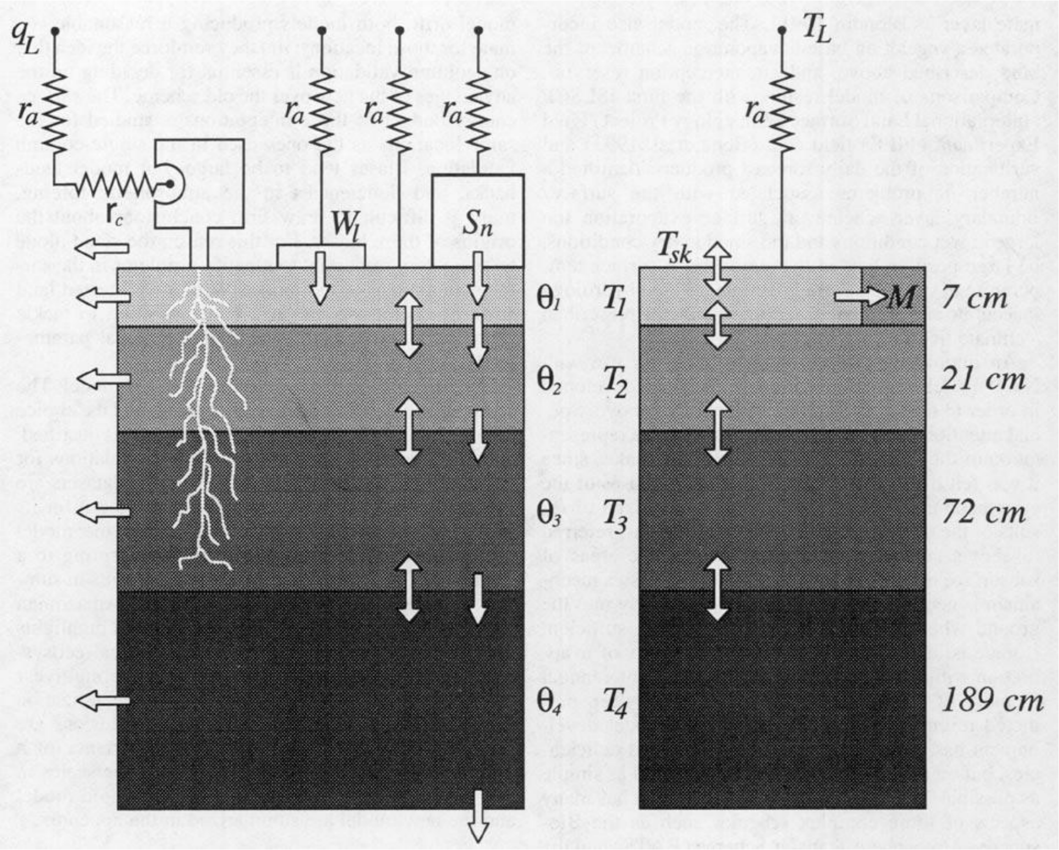
$$\Lambda_{sk}(T_{sk} - T_s) = R_{SW} + R_{LW} + LE + H$$

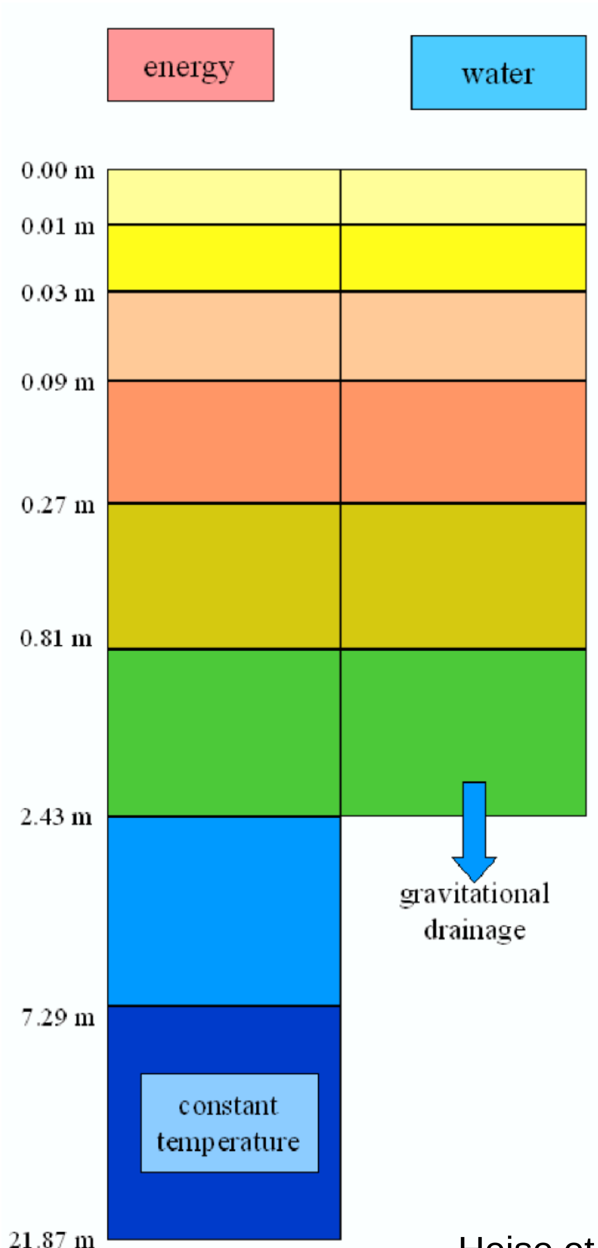
T_{sk}, T_s : skin temperature, surface temperature
Λ_{sk} : skin layer conductivity
R_{SW}, R_{LW} : net shortwave radiation flux, net longwave radiation flux
LE, H : latent heat flux, sensible heat flux

Schulz, J.-P. and G. Vogel, 2020: Improving the processes in the land surface scheme TERRA: Bare soil evaporation and skin temperature, *Atmosphere*, **11**, 513.

Skin temperature in IFS

(Viterbo and Beljaars 1995)





Land surface scheme TERRA

Layers for temperature and soil water content

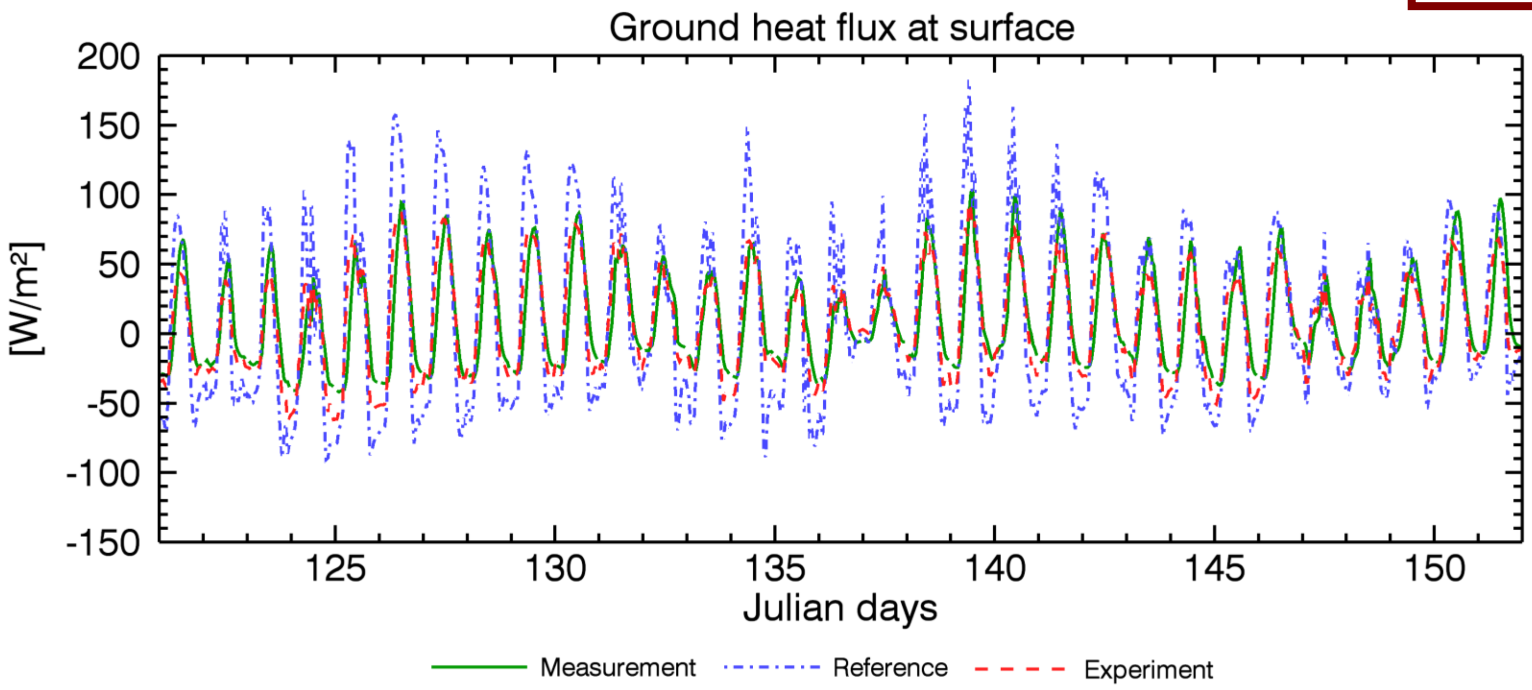
Experiments:

- Use atmospheric forcing to run TERRA in offline mode
- Here, observed forcing from DWD observatory Lindenberg is used (Falkenberg site)

- Reference : TERRA surface temperature
- Experiment: Skin temperature

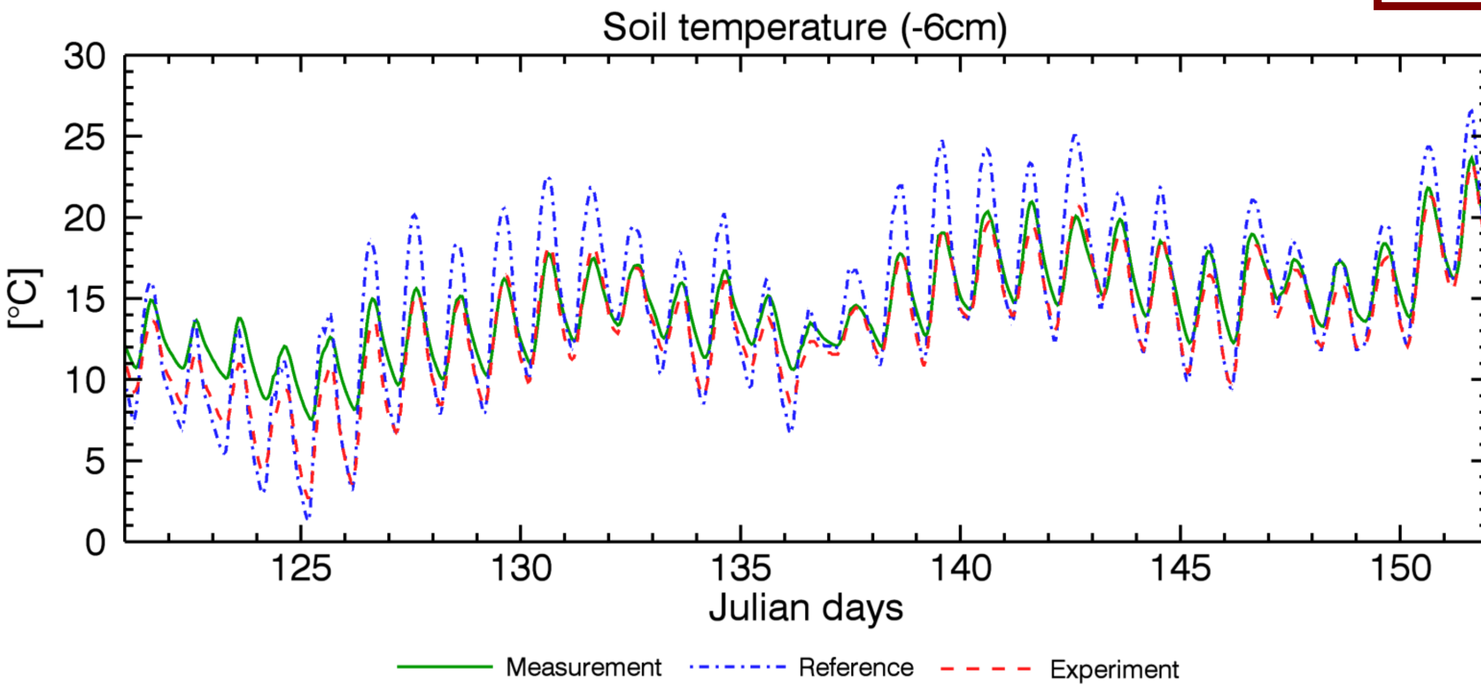
Heise et al. (2006)

May 2011



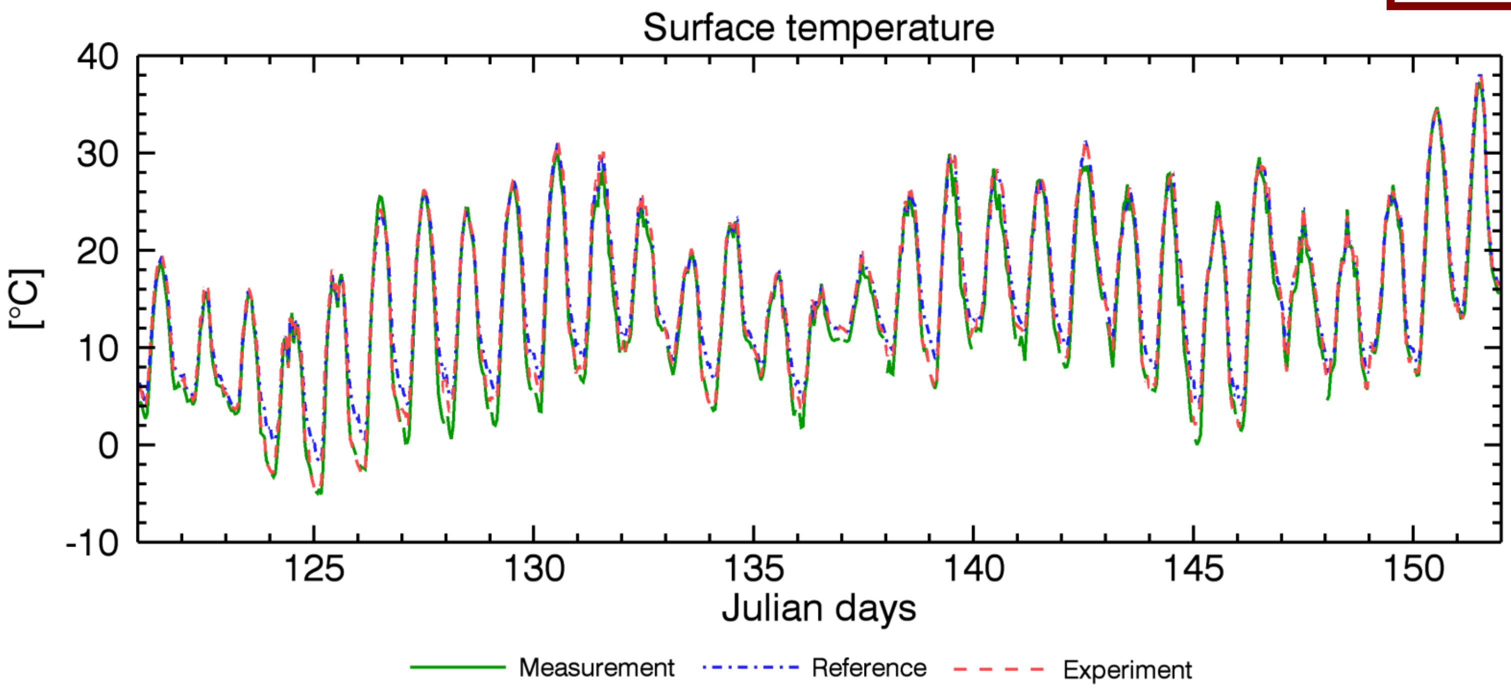
Ground heat flux substantially overestimated by TERRA, with the skin temperature formulation it is significantly reduced and much closer to the measurements

May 2011



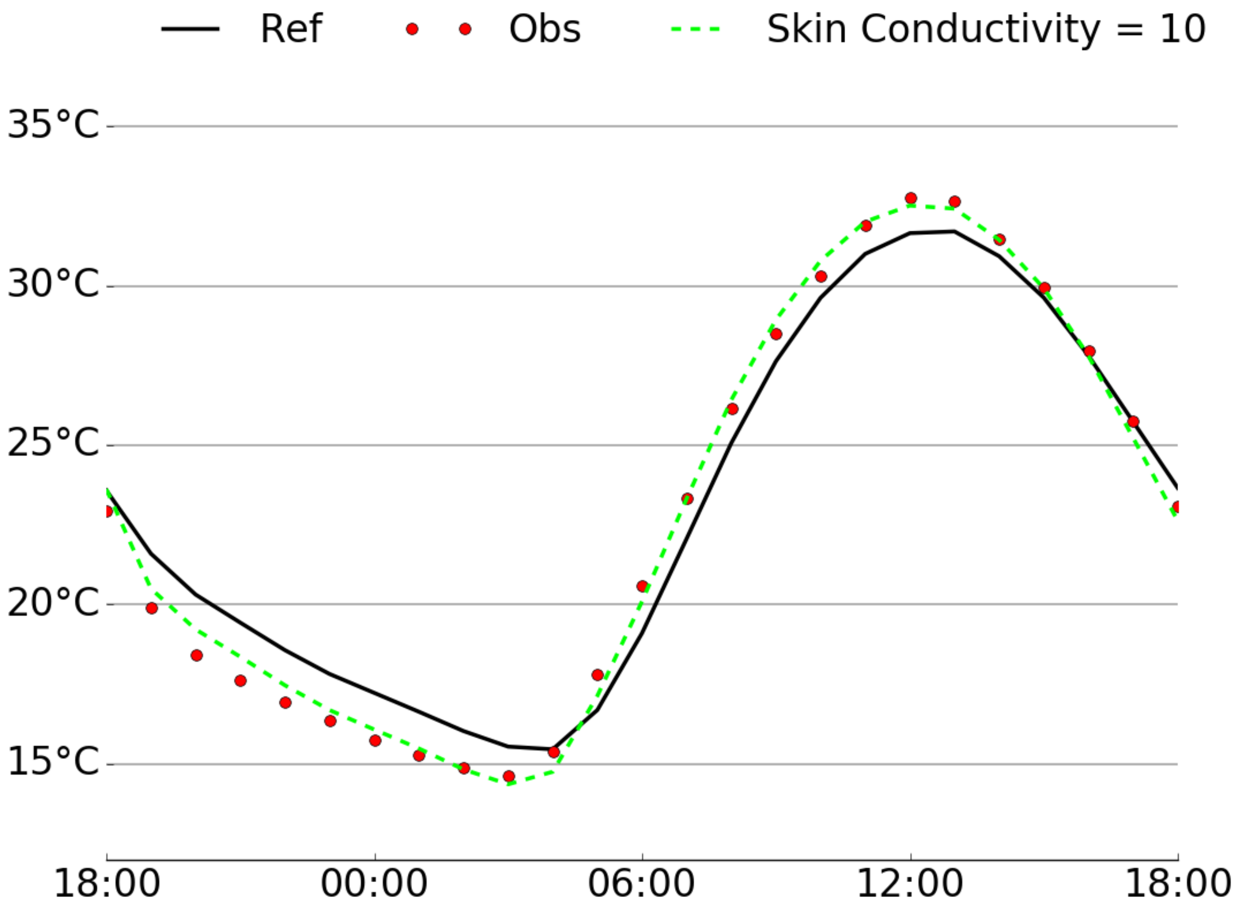
Amplitudes of the diurnal cycles of the soil temperatures in TERRA systematically overestimated, with the skin temperature formulation they are considerably reduced and therefore improved

May 2011



Amplitude of the diurnal cycle of the surface temperature in TERRA systematically underestimated (clear nocturnal warm bias), with the skin temperature formulation it is substantially increased and much closer to the measurements

COSMO-DE: 1 - 2 July 2015



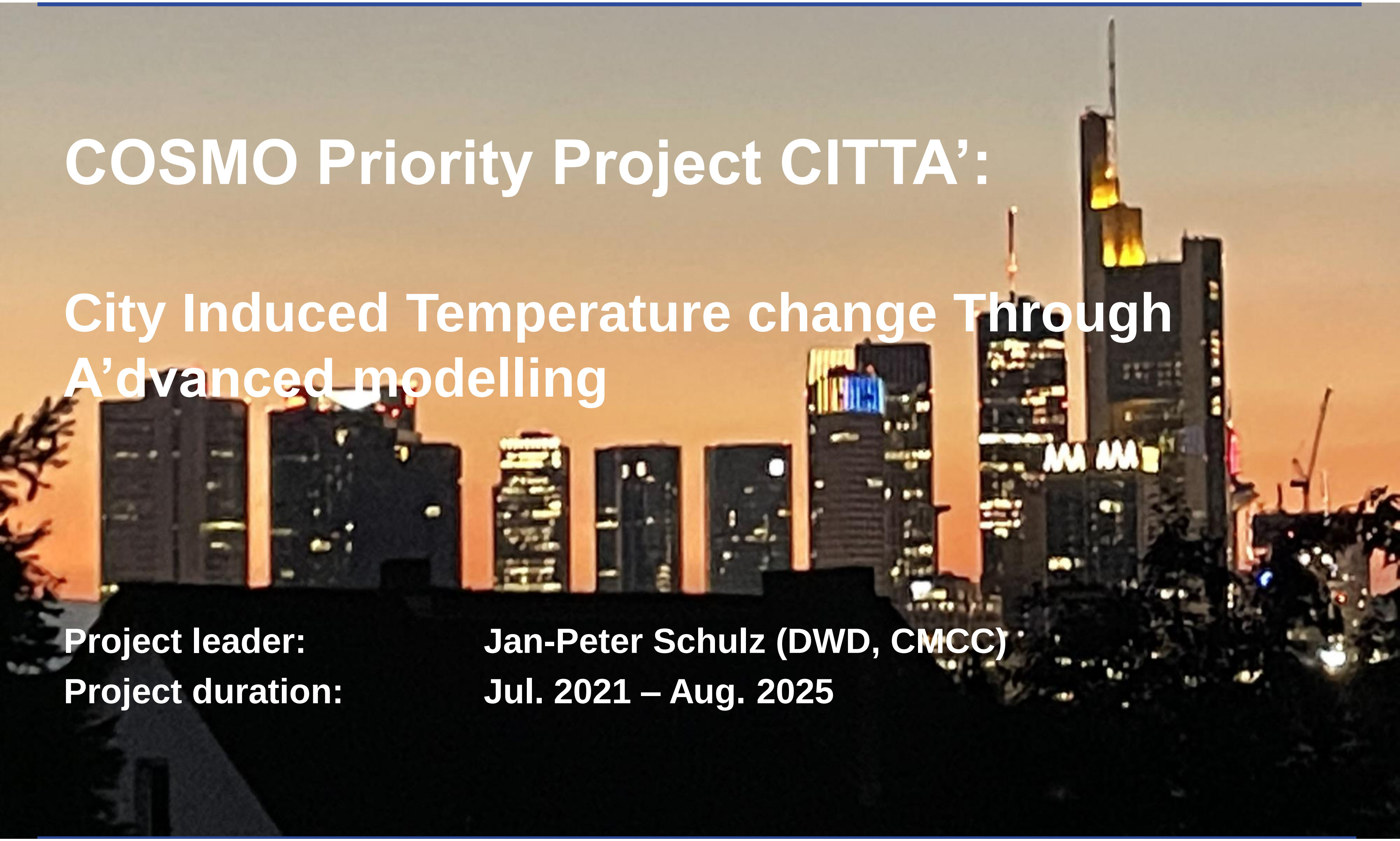
- Obs: Meteosat, cloud free pixels in satellite and model
- Black line: TERRA surface temperature (COSMO-DE)
- Green line: Skin temperature

Christine Sgoff (ZGeoBw)

Amplitude of the diurnal cycle of the surface temperature in TERRA systematically underestimated, with the skin temperature formulation it is substantially increased and much closer to the measurements

Conclusions: Skin temperature

- The amplitude of the diurnal cycle of the surface temperature in TERRA was systematically underestimated.
- The amplitudes of the diurnal cycles of the soil temperatures in TERRA were systematically overestimated.
- The IFS skin temperature formulation was adapted and implemented in TERRA. It provides an additional energy budget for and insulating effects by the vegetation. Experiments in offline mode show substantial improvements with respect to temperature and heat flux errors, and the same in coupled mode.
- The skin temperature is operational at DWD in ICON since May 2020.



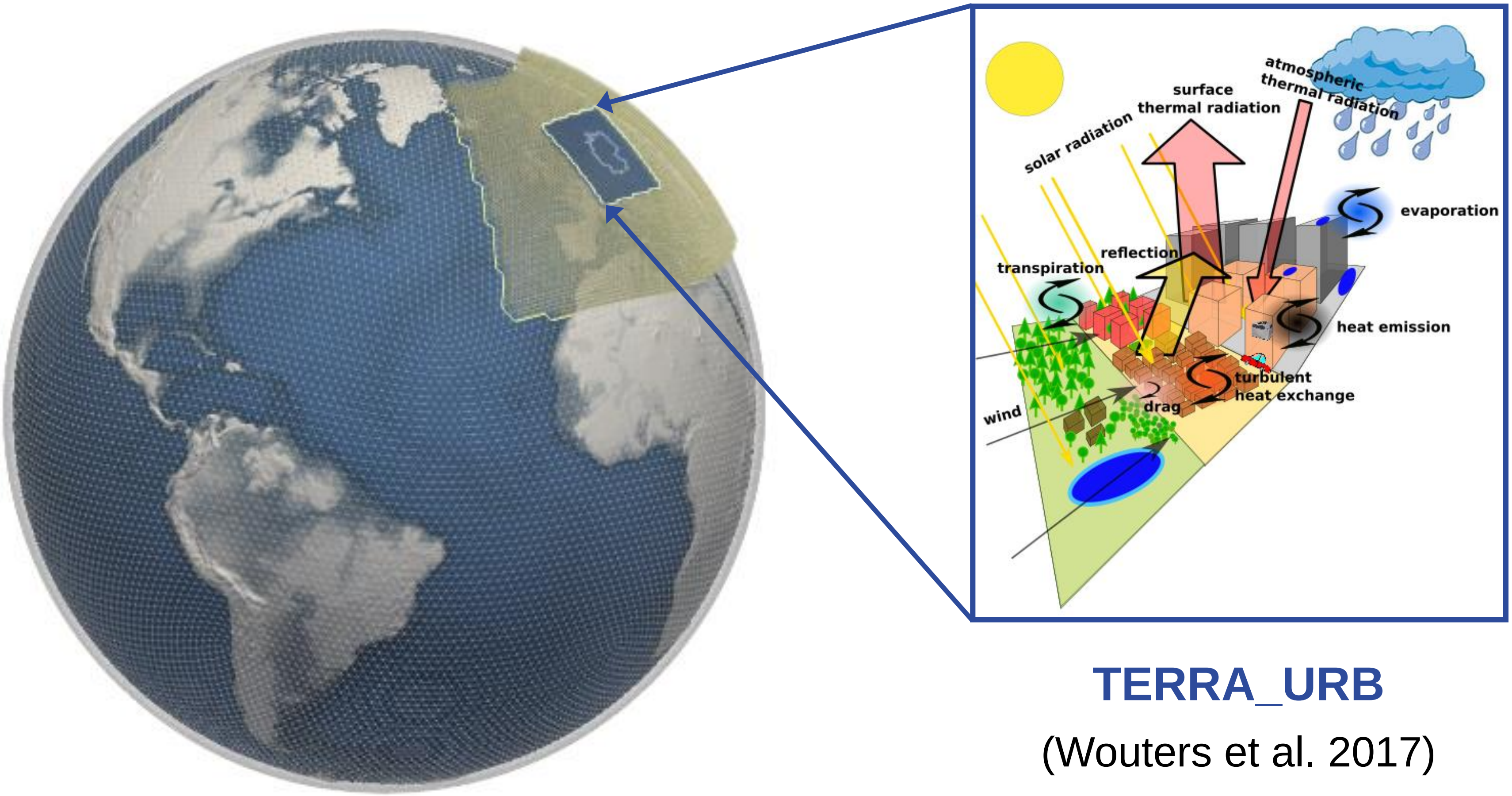
COSMO Priority Project CITTA':

City Induced Temperature change Through A'dvanced modelling

Project leader: Jan-Peter Schulz (DWD, CMCC)
Project duration: Jul. 2021 – Aug. 2025

Photo: J.-P. Schulz

TERRA_URB in ICON

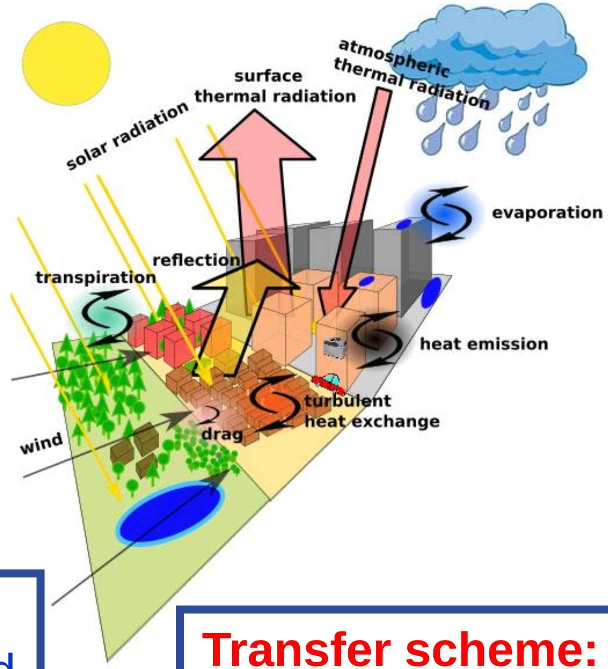


TERRA_URB

(Wouters et al. 2017)

TERRA_URB in ICON

Modifications in ICON:



Land surface scheme:
Introduce puddles
PUDDLE

Radiation scheme:
Modify albedo
ALB

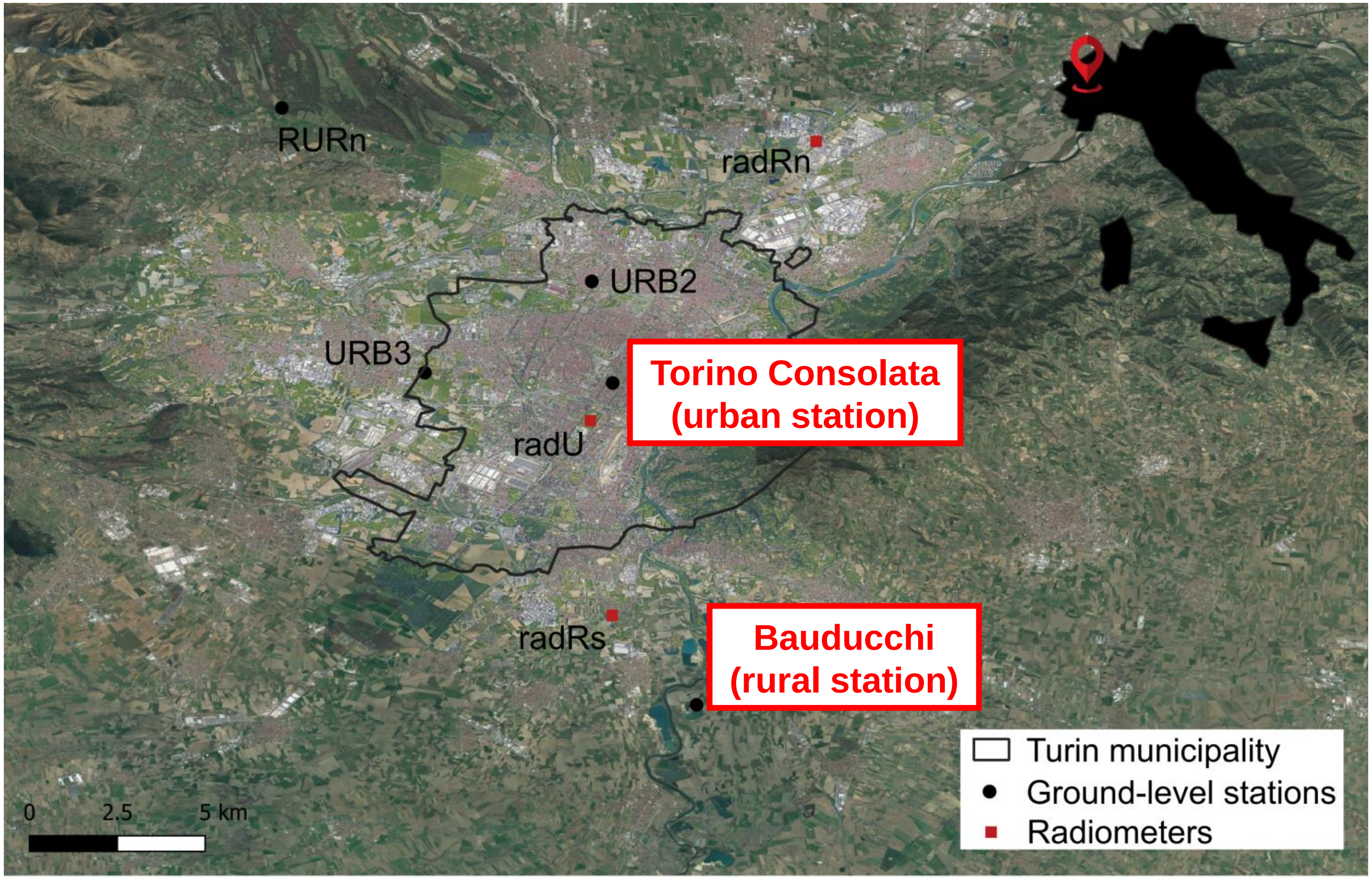
Land surface scheme:
Set infiltration and bare soil evaporation to zero
NOEVAP

Land surface scheme:
Modify heat capacity and thermal conductivity
THERM

Transfer scheme:
Modify thermal roughness length
TURB

Land surface scheme:
Introduce anthropogenic heat flux
HFLUX

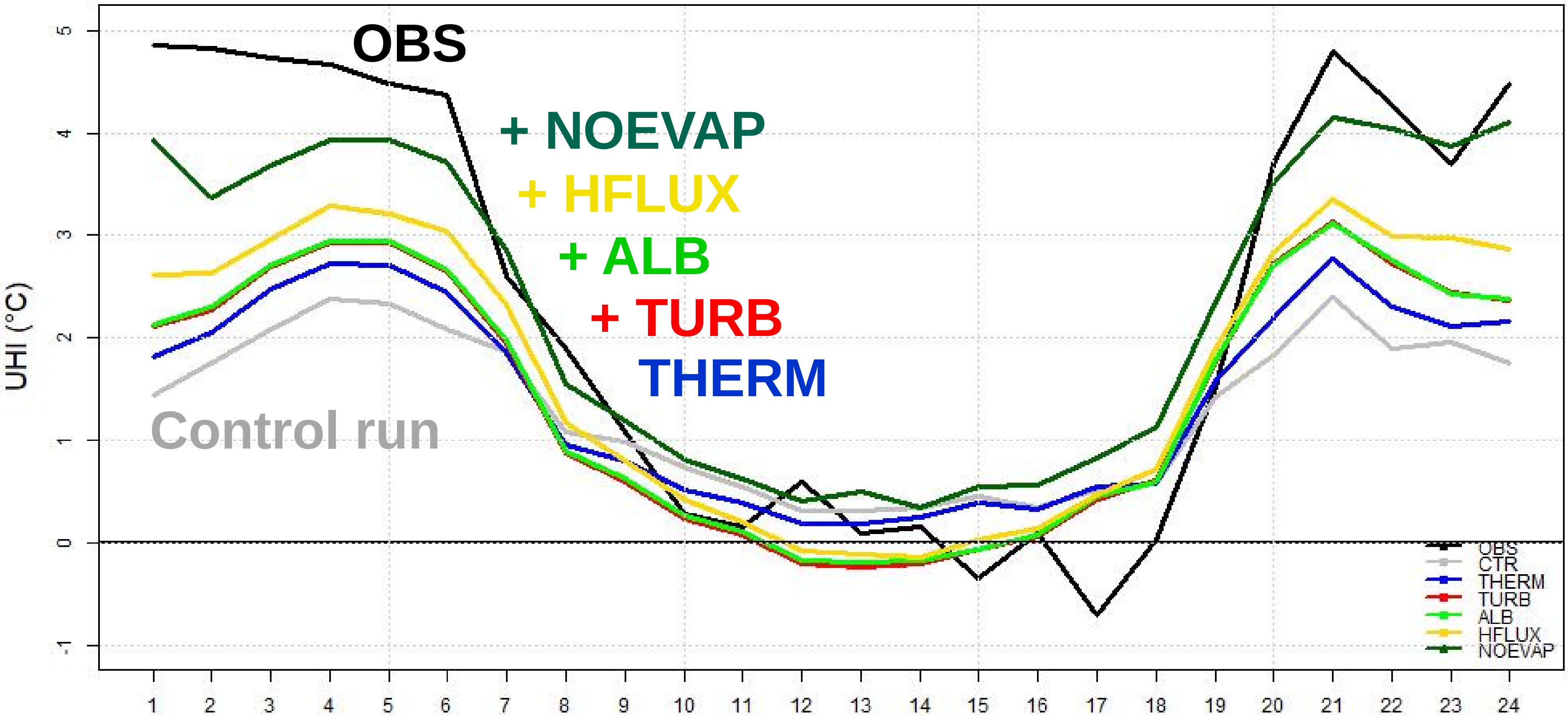
TERRA_URB in ICON



M. Milelli (CIMA), F. Bassani (PoliTo), V. Garbero (ARPAP)

2-m temperature difference: urban – rural

Urban Heat Island (UHI) effect



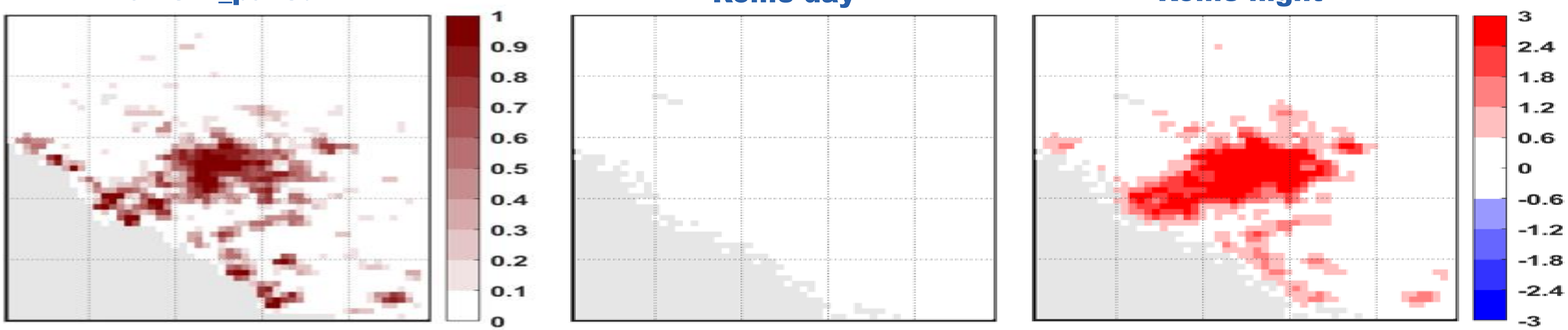
M. Milelli (CIMA), F. Bassani (PoliTo), V. Garbero (ARPAP)

- **Period: 16 - 20 Aug. 2017**
- **TU on = ICON+TERRA_URB on**
- **TU off = ICON (reference case)**

2-m temperature difference: TU on – TU off

Fr_paved = Impervious Surface Area (ISA) | **Day** | **Night**

Rome fr_paved | **Rome day** | **Rome night**



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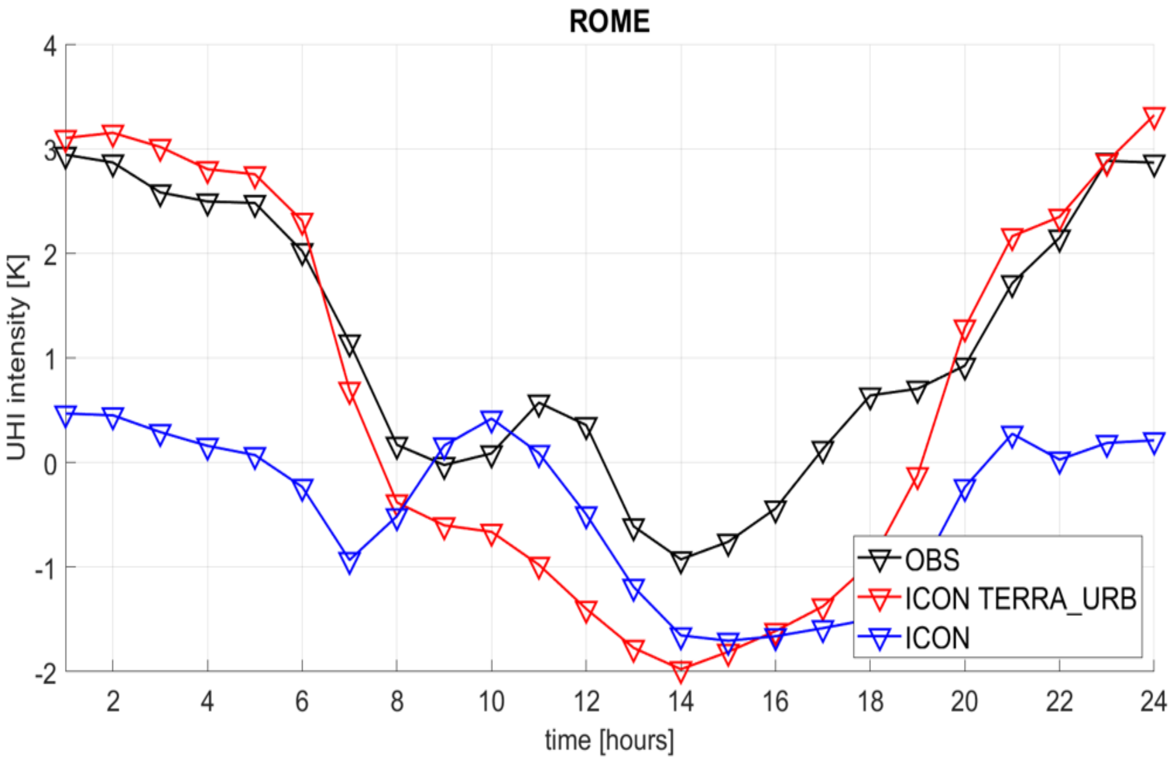
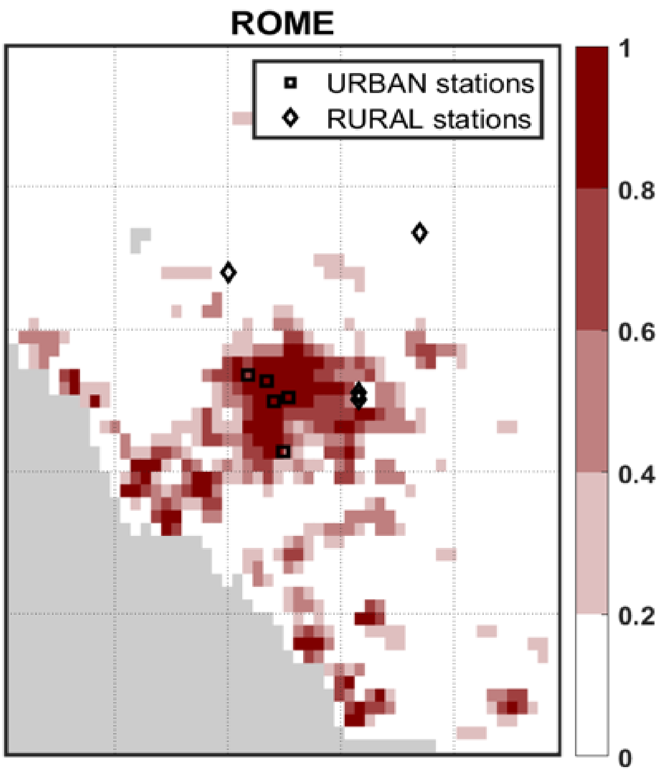




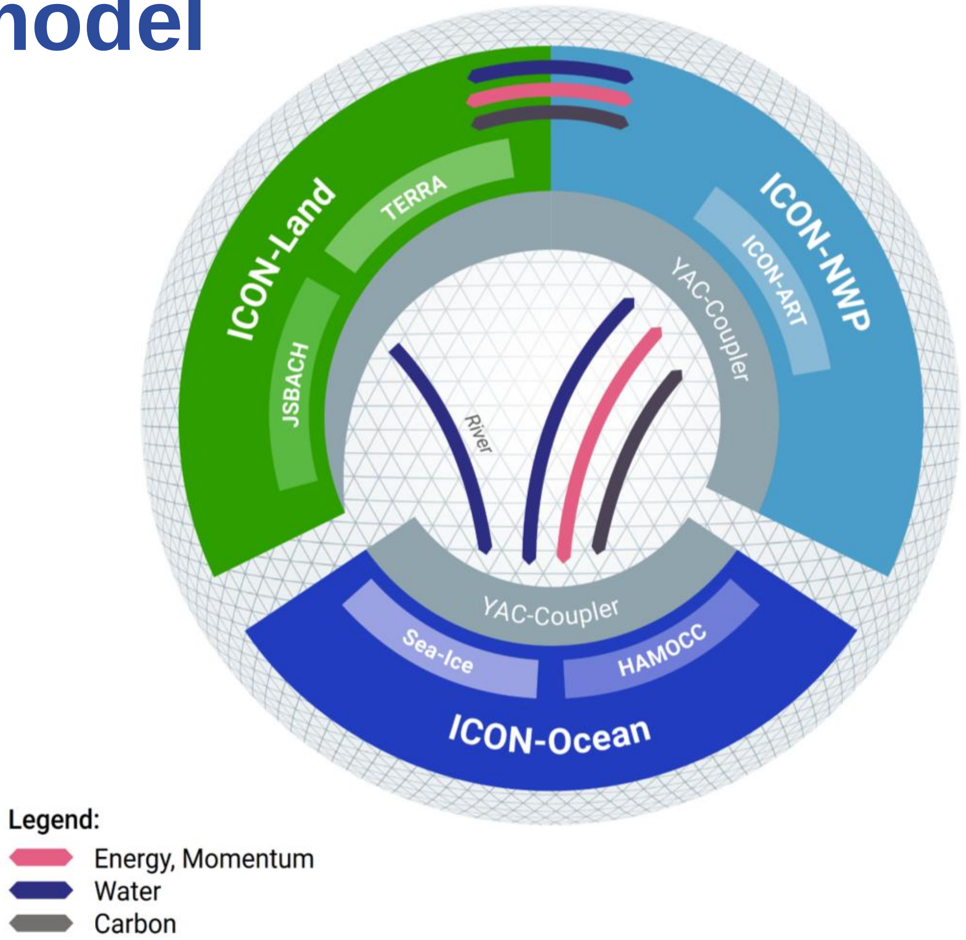
Campanale, A., M. Adinolfi, M. Raffa, J.-P. Schulz, P. Mercogliano, 2025: Investigating urban heat islands over Rome and Milan during a summer period through the TERRA_URB parameterization in the ICON model. *Urban Climate*, **60**, 102335.

Conclusions: TERRA_URB

- TERRA_URB is fully implemented and tested in ICON. It is available in the gitlab icon-nwp master.
- Experiments with TERRA_URB in ICON-LAM are on-going in several groups of the project. The results look very promising.
- Characteristic features of urban surfaces in atmospheric models, for instance the Urban Heat and Dry Island effects, are well represented.
- TERRA_URB is operational at DWD in ICON-D2, ICON-D2-EPS and RUC since February 2025.

Global coupled A-O model

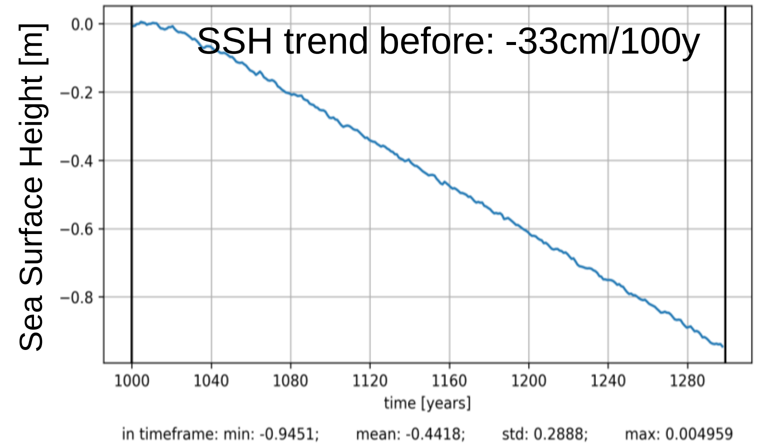
- atmosphere: ICON-NWP
    - TKE (DWD)
    - total turbulent energy (MPI)
- land: TERRA, JSBACH, Quincy
- ocean: ICON-O
- sea-ice
- river routing
- coupler: YAC
- ocean carbon cycle: HAMOCC
- ocean wave model: WAM
- ocean limited area and telescope
- trace gases: ICON-ART

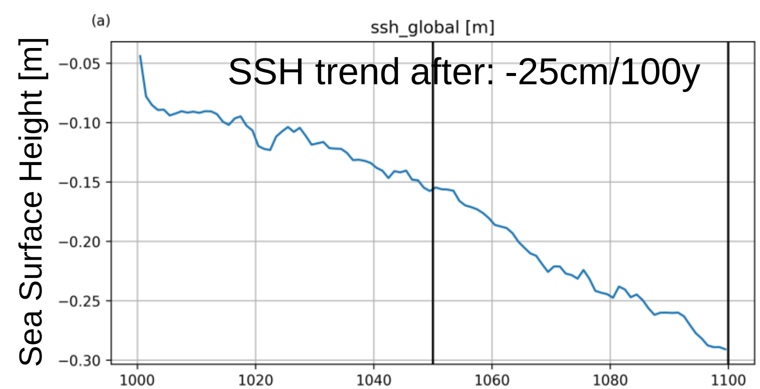


N. Schenk (DWD), M. Köhler (DWD)

The problem …

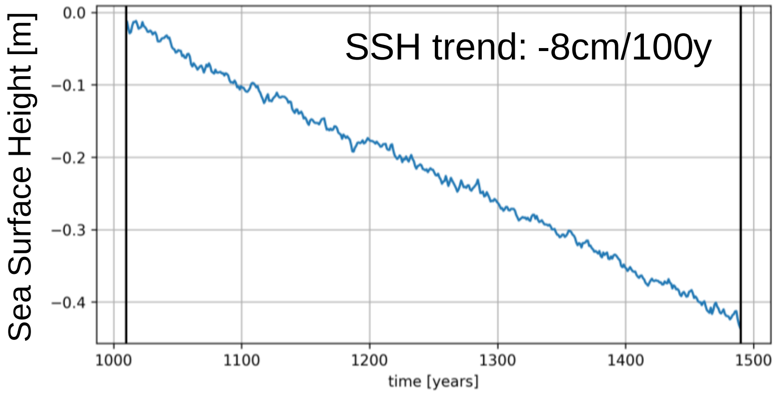
- Significant water budget error, impacts sea surface height (SSH)
- Investigate: Check budget across parts of TERRA
- Findings:
  - Confusion in reference areas, e.g., per m^2 of cell vs. per m^2 of snow cover
  - Units: $m(H_2O)$ vs. kg/m^2
  - Rate vs. change over time step
  - “Bare-soil” evaporation from glaciers
- Result: Water balance improved
- But: Still significant SSH trend. Why?





R. Wirth (DWD), M. Köhler (DWD)

- Water conservation in ICON-NWP atmosphere?
  Already fixed.
- Hydrological discharge model?
  No issues found.
- What else? Physics!
  - Greenland & Antarctica accumulate snow
  - Reason? Missing ice-sheet dynamics. Glaciers do not flow towards ocean
    ➔ No sink for snow on glaciers
  - Fix: Limit snow height to 40 m, put excess precipitation directly into runoff
  - Transient reduction in SSH expected while glaciers fill up to limit
  - Long-term trend still negative



Much improved, but still work to be done ...

R. Wirth (DWD), M. Köhler (DWD)

The problem …

- Near-surface model biases are strongly affected by uncertain physical properties of vegetation and soil (e.g. stomatal resistance, soil thermal conductivity, etc.) as well as model tuning parameters.
- Physical properties are usually derived from external parameter data (land cover classification, soil texture, etc.), which may not cover the full heterogeneity that exists in nature.
- This typically leads to ambivalent results when trying to tune parameters (better in some regions, worse in others).
- At DWD, we developed a methodology to use information from data assimilation (DA) to adaptively optimize uncertain parameters, the **Adaptive Parameter Tuning (APT)**.

Zängl, G., 2023: Adaptive tuning of uncertain parameters in a numerical weather prediction model based upon data assimilation, *Q. J. R. Meteor. Soc.*, **149**, 2861-2880.

Methodology

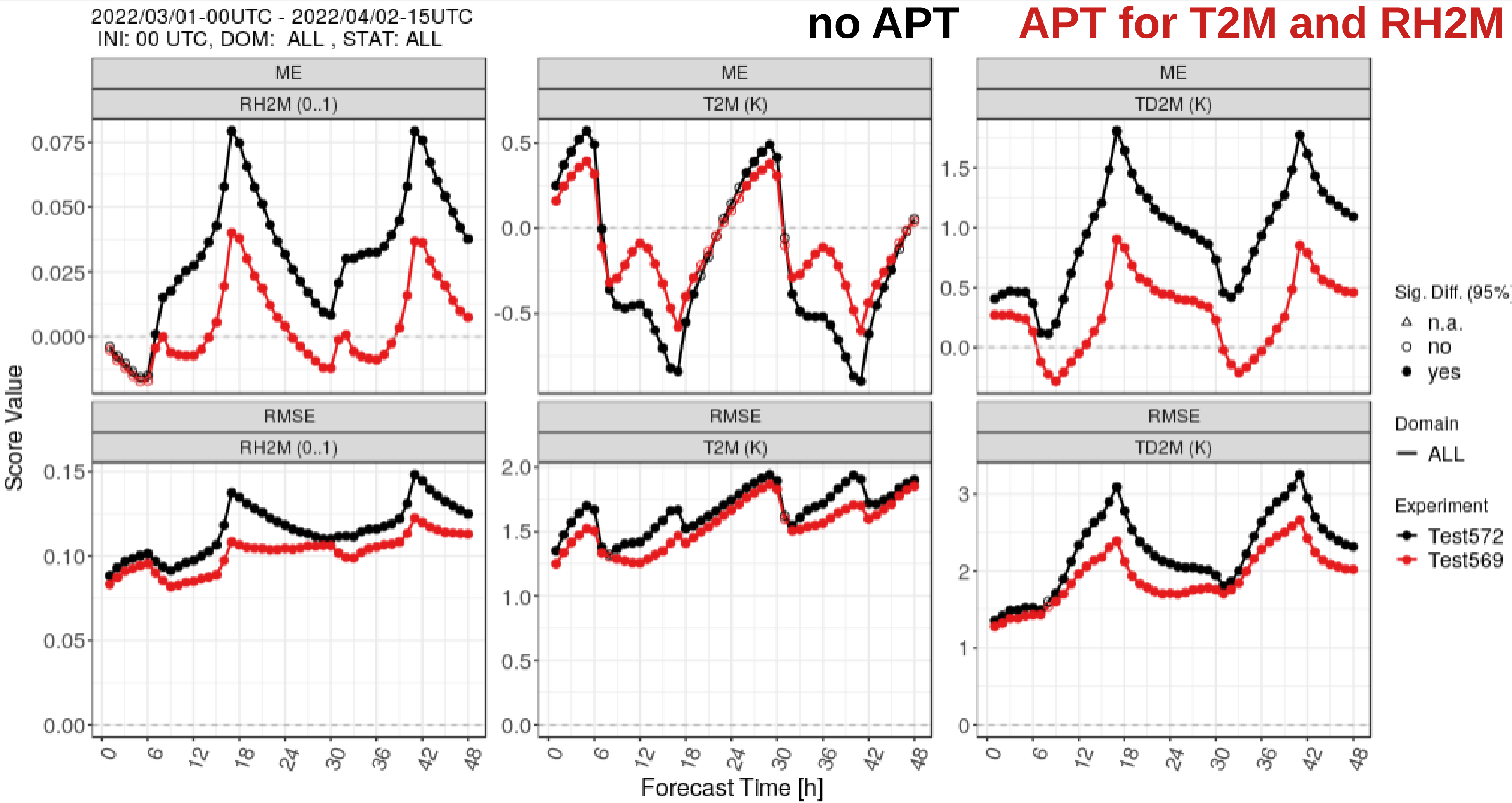
- Forecast variables targeted for adaptive optimization: T2M, RH2M, FF10M.
- Time-filtered data assimilation increments for temperature, humidity and wind speed at the lowest model level are used as proxies for the model bias / predictors for adaptive optimization (filtering time scale 2.5 days).
- This obviously requires assimilation of T2M, RH2M and FF10M data.
- In the global system, the adaptive optimization of T2M was put into operations in May 2022, together with the assimilation of T2M.

Model parameters selected for APT

- T2M/RH2M: Stomatal resistance of vegetation, minimum resistance of bare soil evaporation
- T2M diurnal amplitude: Soil heat capacity and thermal conductivity, skin layer conductivity, near-surface profiles of minimum vertical diffusion coefficient
- T2M in the presence of snow cover: Snow albedo (and sea-ice albedo over sea ice in the vicinity of coasts)
- FF10M: Vegetation roughness length, SSO blocking tendency at lowest model level

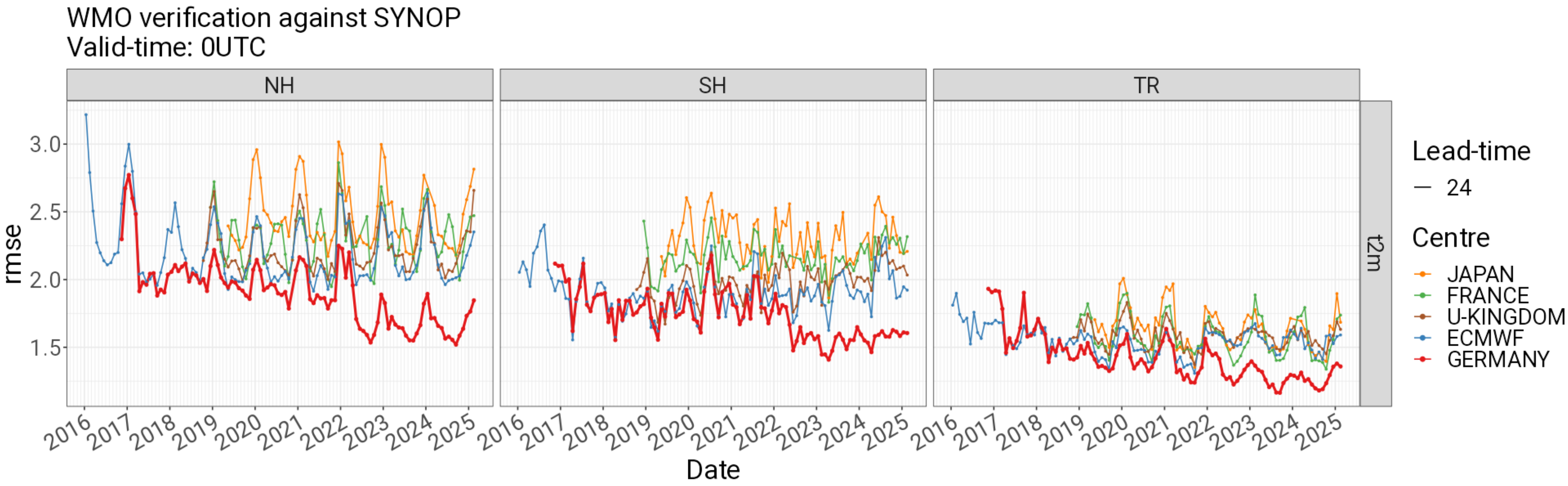
ICON-D2 (LAM configuration for central Europe), March 2022

no APT **APT for T2M and RH2M**



WMO (WGNE) intercomparison for SYNOP scores

2-m temperature, 24-h forecasts at 00 UTC



DWD ECMWF UKMO Météo France JMA