

COSMO Working Group Physics Overview

Jan-Peter Schulz^{1,2}

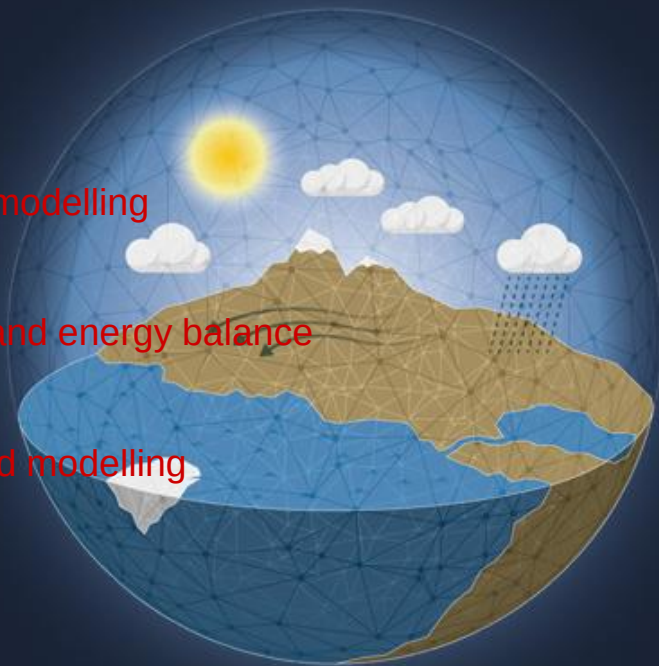
¹German Meteorological Service, Offenbach am Main, Germany

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COSMO General Meeting, 14-18 Sep. 2026, Rome, Italy

Outline

- Urban modelling
- Water and energy balance
- Coupled modelling





COSMO-GM, Rome 14-18 September 2026

Synergies among Urban Heat Islands, Urban Dry Islands, and Heat Stress during heatwaves: evidences from the Bologna case study using the urbanized ICON model

A. Campanale¹, S. Oliva¹, M. Adinolfi¹, J.-P. Schulz^{2,1}, M. Raffa¹, P. Mercogliano¹

(1) Euro-Mediterranean Center on Climate Change (CMCC), REMHI Division, Caserta, Italy

(2) German Meteorological Service (DWD), Research and Development, Offenbach a. M., Germany

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Outline of the presentation

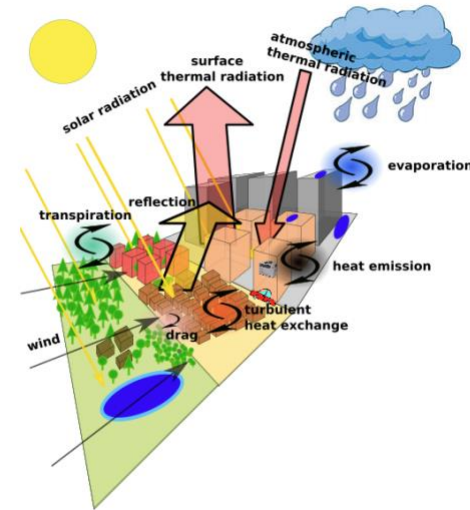
PP_CITTA: an history of success

- The establishment of TERRA_URB

TERRA_URB for climate applications:

- Bologna case study area and simulations setup
- UHI and UDI
- Coupling between UHI/UDI and heatstress with heatwaves

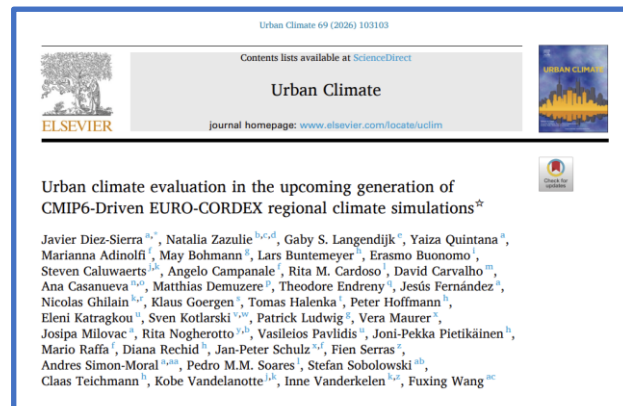
Conclusions and next steps



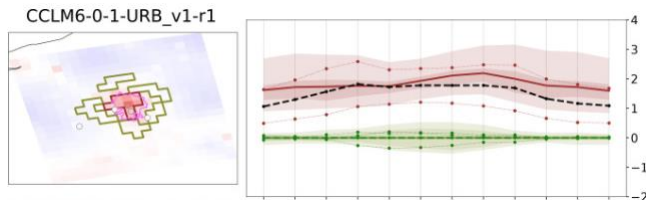
PP_CITTA, a history of success

The successful porting of TERRA_URB from COSMO to ICON demonstrates PP_CITTA's ability to develop and transfer advanced urban modelling capabilities within the ICON framework.

In a recent publication in *Urban Climate* on the evaluation of the next-generation EURO-CORDEX ensemble using different regional climate models, the COSMO-CLM model with the TERRA_URB parameterization was shown to capture key urban climate features, achieving performance comparable to, or even better than, more sophisticated urban parameterizations such as TEB or BEM-BEP. Read more at [10.1016/j.uclim.2026.103103](https://doi.org/10.1016/j.uclim.2026.103103).



Annual cycle of the UHI in Paris simulated with CCLM. The UHI from observations is shown in black, while the CCLM results are shown in red



Bologna case study area

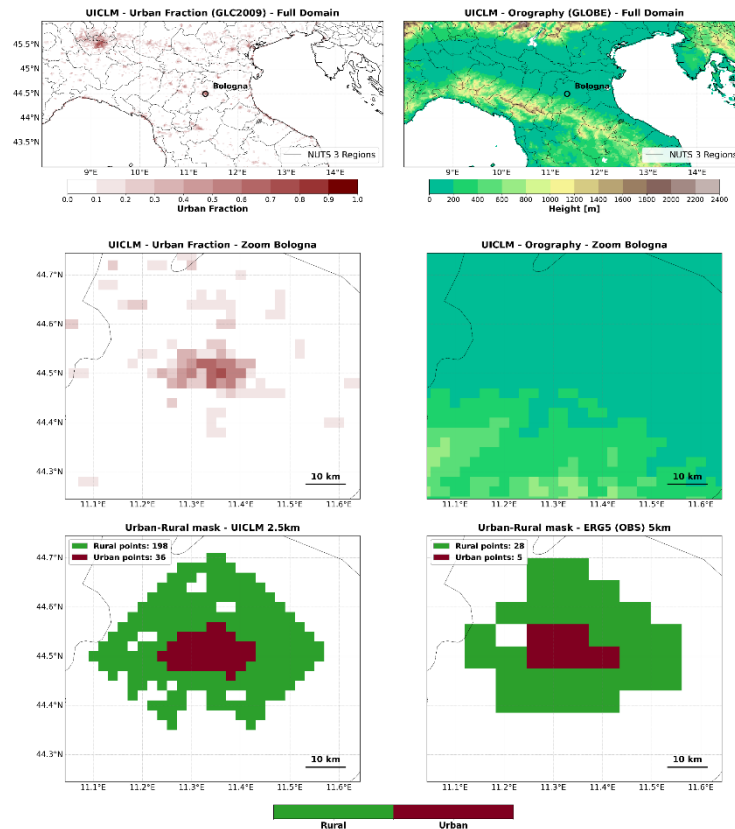


In the EU-funded **CARMINE** project, the **Bologna** area was selected as a case study because one of the main issues addressed is the coupling between the Urban Heat Island (UHI) effect and heatwaves, and its impact on vulnerable populations.

Model	ICON-CLM with TERRA_URB (UICLM)
Version	ICON release-2025.10-public
Boundary forcing	ERA5 reanalysis 0.25°x 0.25° (≈31 km)
Lateral Boundary Condition (LBC)	update frequency 6 h
Simulated Period	2018-2024 (2018 as spinup)
Soil initializations	Temperature and moisture obtained by interpolation from ERA5
Horizontal resolution	0.0225° (≈2.5 km), R2B10 grid
Time step	20 s
N° vertical levels	65 (top model level elevation = 22 km)
Output frequency	1 h
Land surface scheme	Tiled TERRA (Schrodin and Heise, 2001; Schulz et al., 2016; Schulz and Vogel, 2020) with TERRA_URB parameterization (Wouters et al., 2016; Campanale et al., 2025)
Land use dataset	GlobCover2009 (Arino et al., 2012)
Evaluated variables	2m temperature (T_2M) and 2m relative humidity (RH_2M)

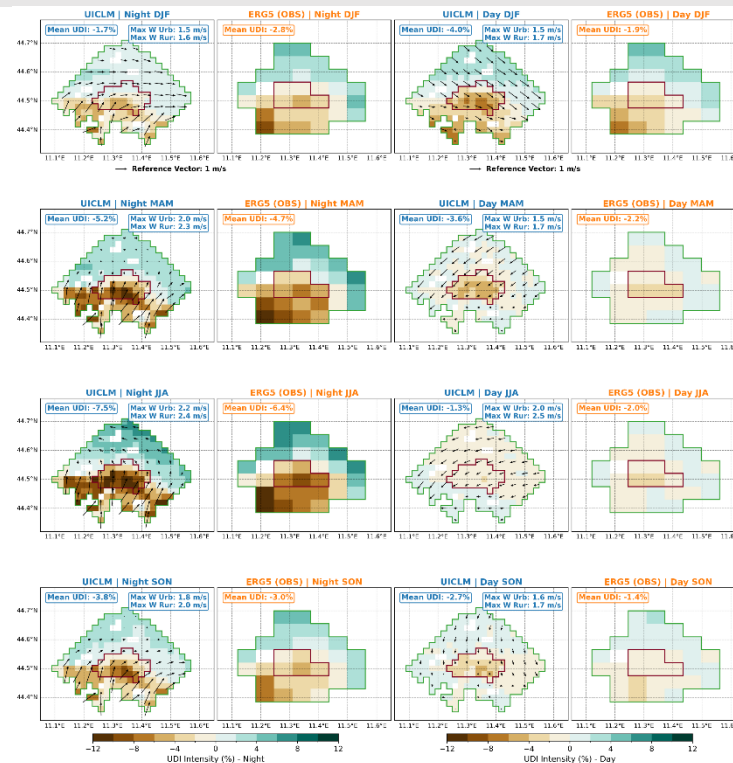
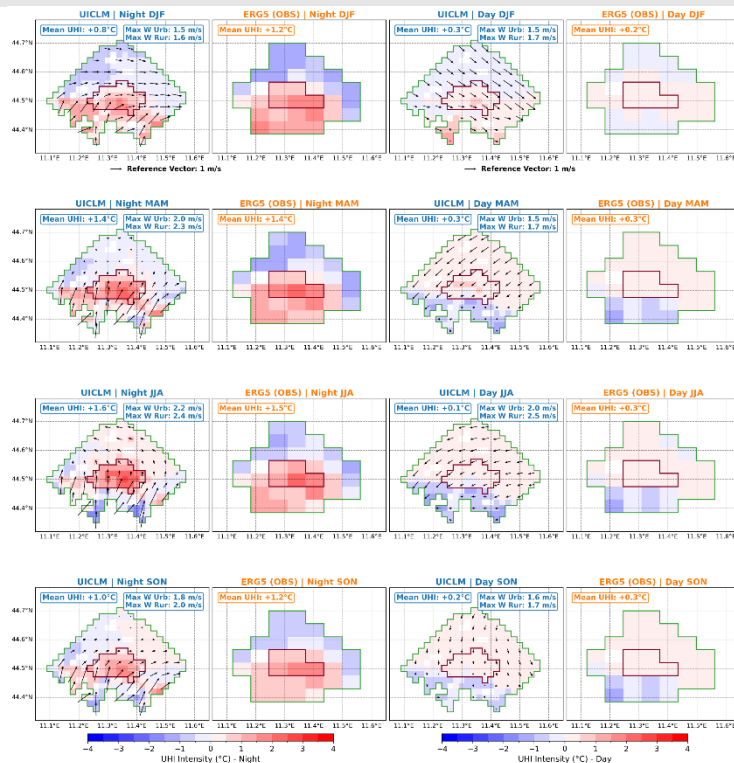
Setup used for the climate simulations. The most important activated parameterizations are based on the ICON-D2 configuration.

The urban–rural mask was created using the algorithm provided by Diez-Sierra et al. (2025).



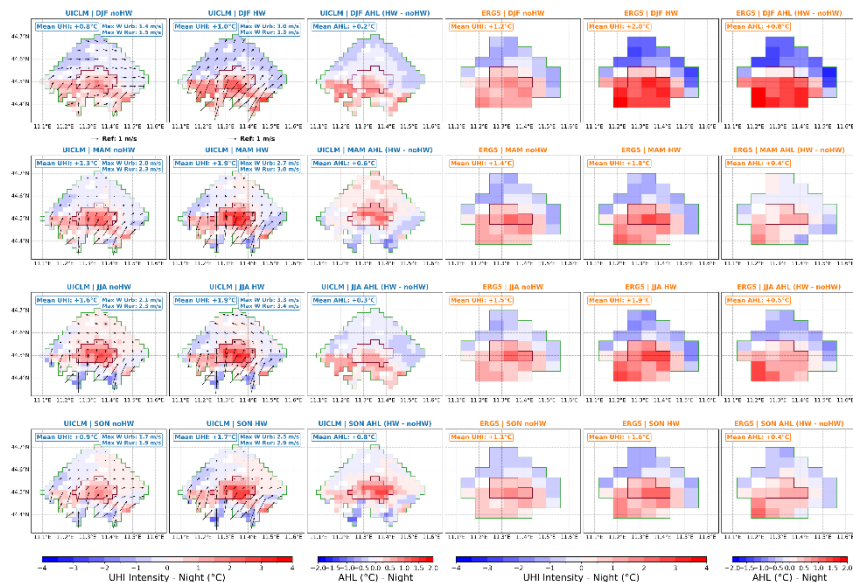
Urban-rural masks obtained for UICLM and ERG5 (observational dataset)

UHI and UDI representation



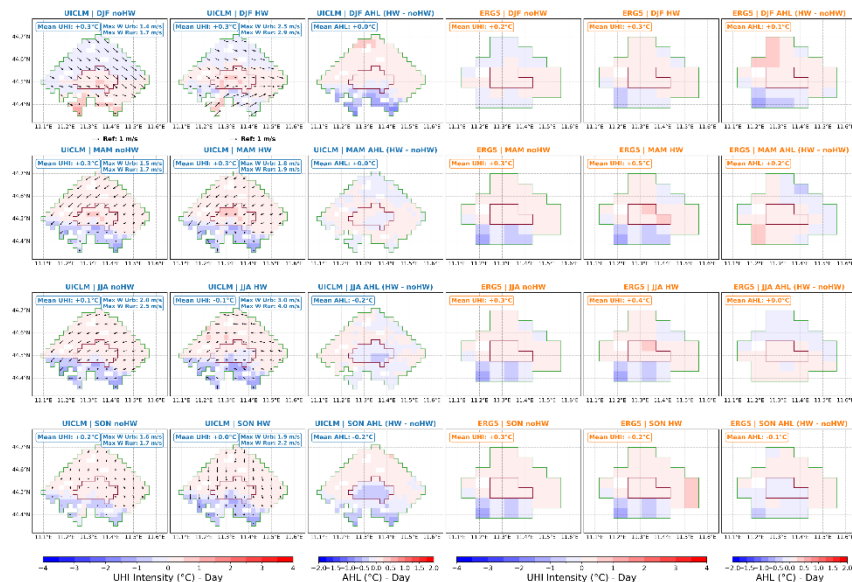
The spatial representation of UHI and UDI is obtained by subtracting the mean temperature and relative humidity values, averaged over rural points, from the corresponding temperature and relative humidity fields for both UICLM and ERG5.

UHI amplification



Spatial representation of nocturnal UHI during HW and no-HW conditions for both UICLM and ERG5. The AHL (Added Heat Load) is defined as the difference between UHI|HW and UHI|no-HW, showing the increase in UHI intensity during HW conditions.

Heatwaves amplify nocturnal urban effects, with UHI reaching +1.9 °C in both UICLM (compared with +1.3 °C during noHW) and ERG5 (compared with +1.4 °C during noHW) during JJA, while showing weak or no amplification during the day.



Spatial representation of diurnal UHI during HW and no-HW conditions for both UICLM and ERG5. The AHL (Added Heat Load) is defined as the difference between UHI|HW and UHI|no-HW, showing the increase in UHI intensity during HW conditions.

- UICLM reproduces the main urban climate features of the Bologna metropolitan area, capturing the seasonal and diurnal variability of UHI and UDI (paper in preparation; more details will be provided in that study).
- UHI is predominantly nocturnal, reaching +1.6 °C in UICLM vs +1.5 °C in ERG5 in summer, while daytime urban–rural differences remain weak. UDI is also stronger at night, reaching –7.4% in UICLM vs –6.2% in ERG5 under all weather conditions.
- Summer heatwaves amplify nocturnal urban effects, with UHI reaching +1.9 °C in both UICLM and ERG5, and UDI reaching –9.2% in UICLM vs –9.0% in ERG5.
- Thermal stress intensity is mainly driven by synoptic heatwave forcing during the day, whereas urban effects become more relevant at night, increasing the frequency and persistence of higher-risk conditions.
- Despite summer warm and dry biases during day, urban–rural contrasts are well captured, with UHI and UDI showing close agreement between UICLM and ERG5, indicating that the main mechanisms governing urban effects are well represented.
- UICLM provides a suitable framework for high-resolution urban climate studies, with potential applications to future climate projections and the assessment of compound heatwave, UHI and UDI impacts.
- Next steps: extend the analysis to climate projections to investigate whether UHI/UDI-heatwave interactions and associated thermal stress intensify under future warming, supporting the assessment of urban climate risks and adaptation strategies.

Thank you for your attention!
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Evaluation of ICON-2I with TERRA-URB across Winter and Summer Seasons

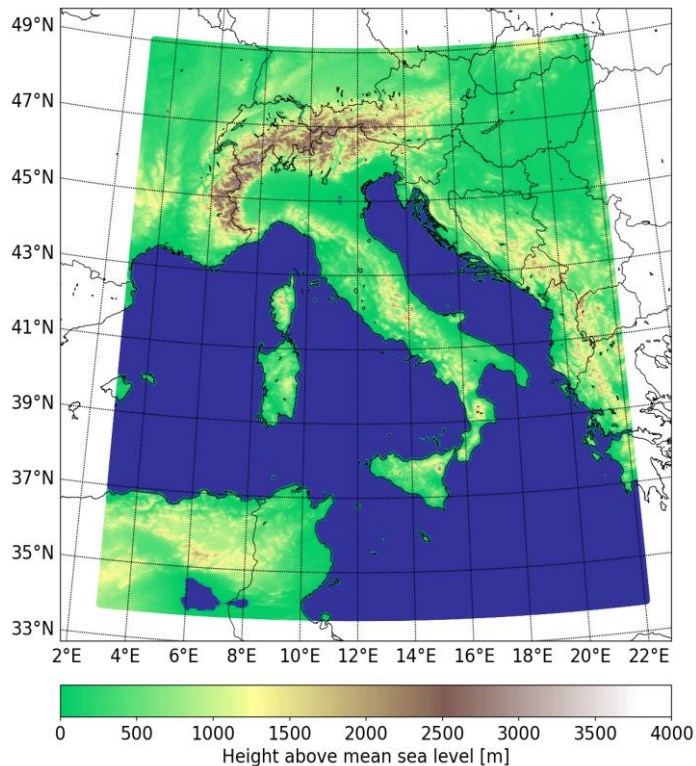
L. Mattavelli¹, T. Gastaldo¹, J.-P. Schulz^{2,3}, V. Poli¹, D. Cesari¹, E. Minguzzi¹, C. Marsigli¹

¹ ARPAE, ² DWD, ³ CMCC

COSMO General Meeting, September 14th-19th 2026, Rome

Introduction

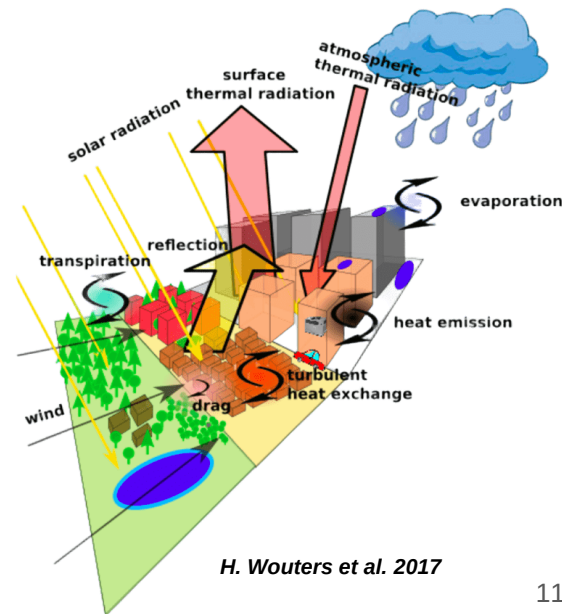
ICON-2I: main operational model at ARP AE



- 2 km grid step
- BC from IFS

- continuous DA based on Kenda
- **No urban parametrization**

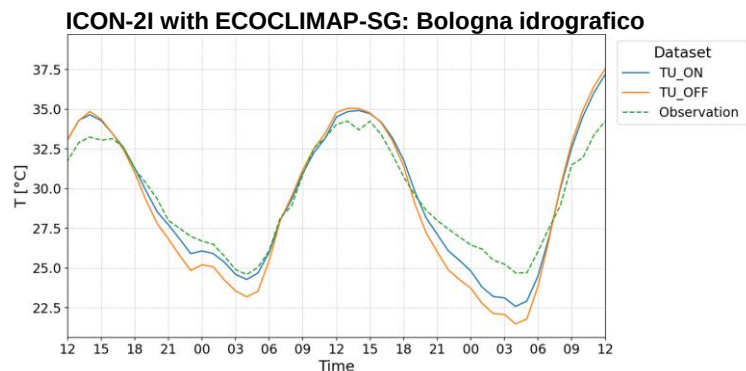
TERRA_URB



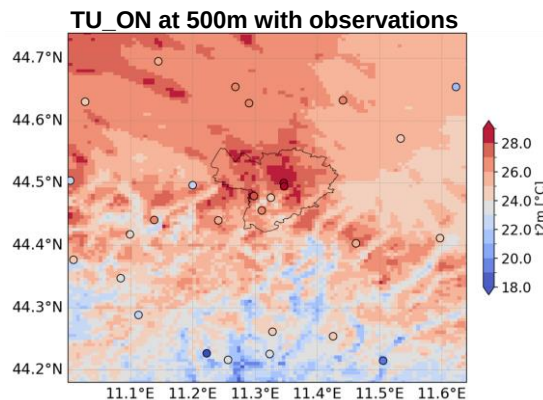
Objective

TERRA_URB has shown significant improvements in capturing the Urban Heat Island (UHI) effect (COSMO Priority Project CITTA')

In the last year at ARPAE multiple urban analysis under different configurations



"First tests with Zonda for ECOCLIMAP-SG in ICON", COSMO GM 2025 - Basel



"Hectometric-scale urban simulations with ICON in Emilia-Romagna", ICCARUS 2026 - DWD, Offenbach am Main

Evaluate the performance of TERRA_URB with ICON-2I
over the full operational domain

Simulation setup

- ICON-2I operational configuration
- Land cover dataset: GLOBCOVER 2009
- **TERRA_URB old configuration:**
- Runs at 00 UTC and 12 UTC
- + 72h
- Operational KENDA (no TERRA_URB)

lterra_urb	.TRUE.
itype_ahf	1
tune_urbahf	15., 0., 0., 15.
tune_urbisa	1.0, 1.0

Simulation period:

- 01/12/2024 - 31/01/2025: **winter** period, many nights characterized by strong UHI
- 20/05/2026 - 19/07/2026: **summer** period, multiple HWs

Observations: local ARPAE weather stations

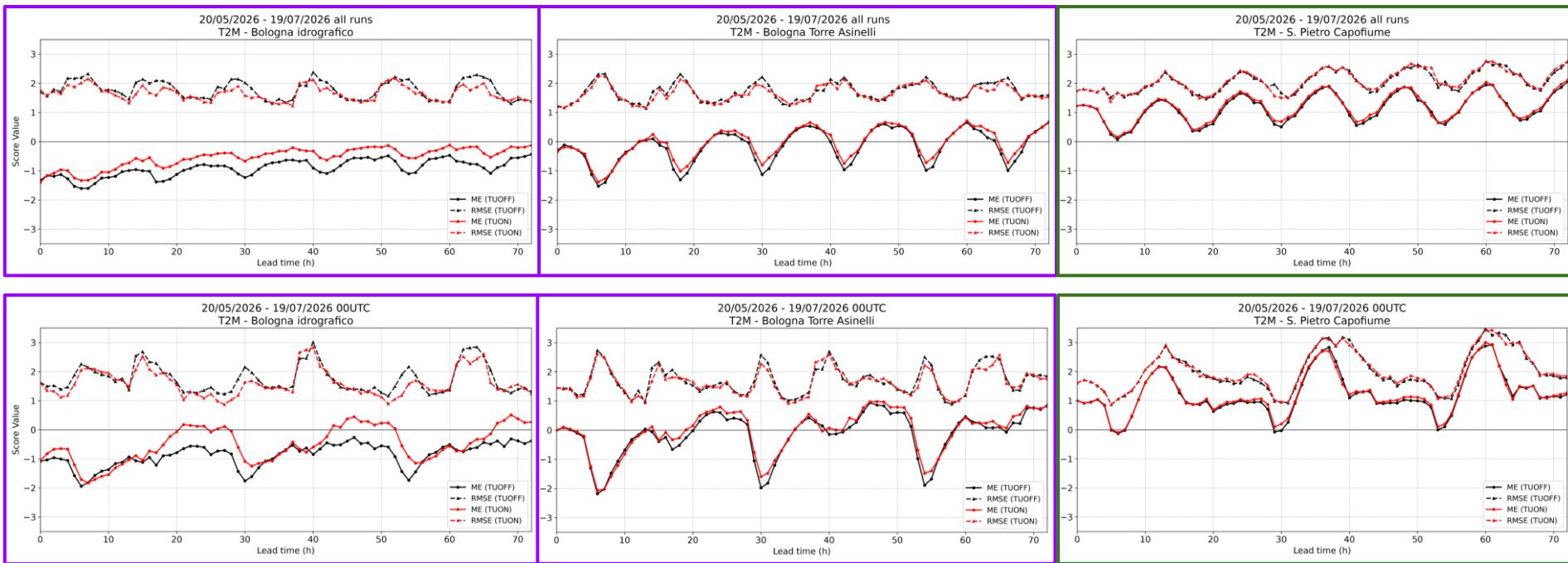
urban observations



value at 2m

Obs. height $\geq$ lowest model level $\xrightarrow{\text{interpolation between model levels}}$

Bologna: summer period

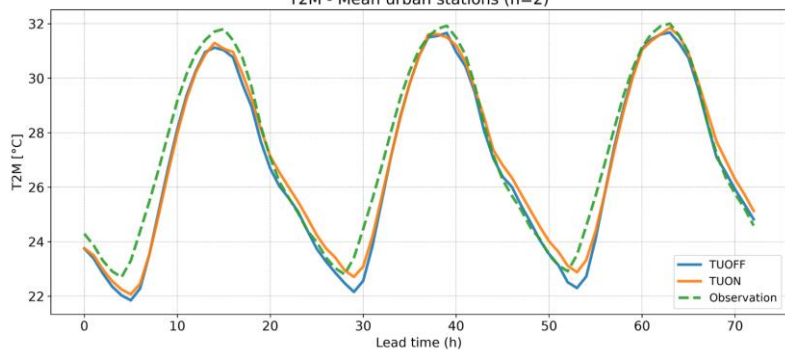


- Urban effect occurs mainly during nighttime, as expected
- Improvement in scores due to TERRA_URB is slightly better compared to the winter season
- Smaller impact observed at Torre Asinelli station

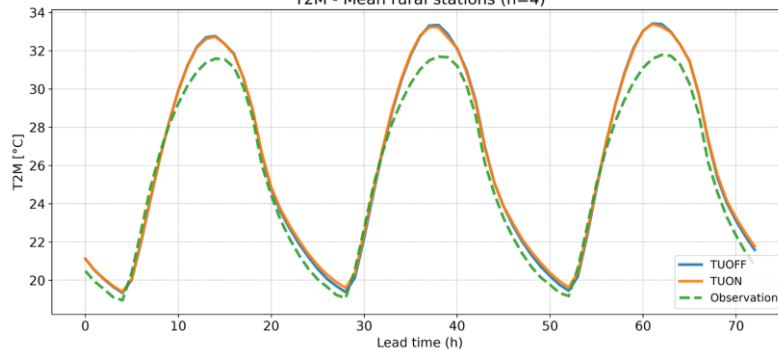
- Diurnal bias is stronger during the summer season with maximum at 12 UTC

Bologna: summer period - 00 UTC

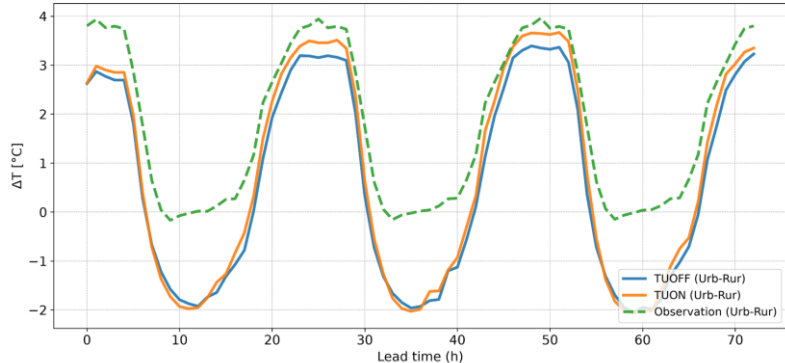
20/05/2026 - 19/07/2026 - Time series
T2M - Mean urban stations (n=2)



20/05/2026 - 19/07/2026 - Time series
T2M - Mean rural stations (n=4)



20/05/2026 - 19/07/2026 - UHI effect



- Big overestimation of T2M over rural by both configurations
- TERRA_URB improves nighttime temperature, though a slight mean underestimation persists
- Delayed morning warming: ICON delays the temperature rise after the nighttime minimum compared to observations

Over Bologna:

- **Winter:** **small improvement** by TERRA_URB with an impact is small but persistent throughout the diurnal cycle
- **Summer:** Nighttime impact is stronger, leading to **improvement in RMSE and ME**, though temperatures remain slightly underestimated
- Daytime UHI: False negative UHI observed, driven by the **overestimation of max T2M** in rural areas
- **Timing:** Delayed morning warming is evident when using the model-level interpolation approach

Over smaller cities:

- Significant TERRA_URB impact observed
- Consistent improvement in overall scores

Next steps

- Expand the analysis to other Italian cities and evaluate additional variables (Relative Humidity)
- FFV2 evaluation (SYNOP stations), precipitation verification and focus on Turin (collaboration with ARPAP & CIMA)
- Investigate the daytime T2m overestimation in Po Valley rural areas
- Continue testing TERRA_URB at the hectometric scale and comparison with different models (collaboration with the University of Bologna - presentation: Nagaraju et al.)



Empa

Materials Science and Technology



The BEP-Tree Urban Canopy Model Coupled with ICON

Kutay Dönmez and Dominik Brunner

Empa – Swiss Federal Laboratories for Materials Science and Technology

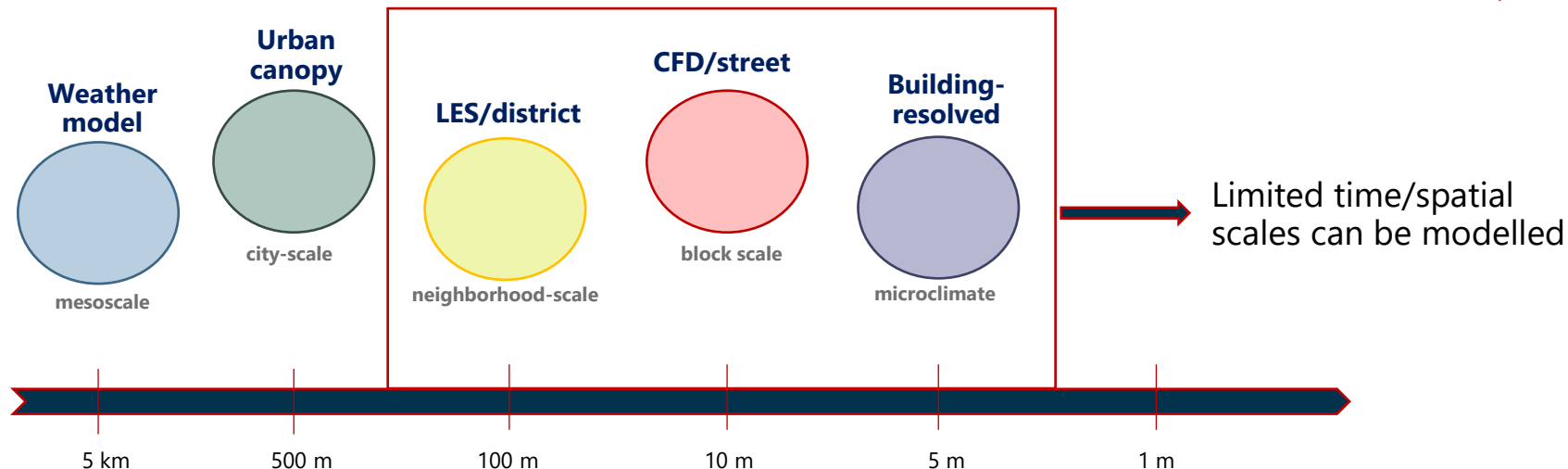
Laboratory for Air Pollution / Environmental Technology

Dübendorf, Switzerland

COSMO General Meeting

09-2026

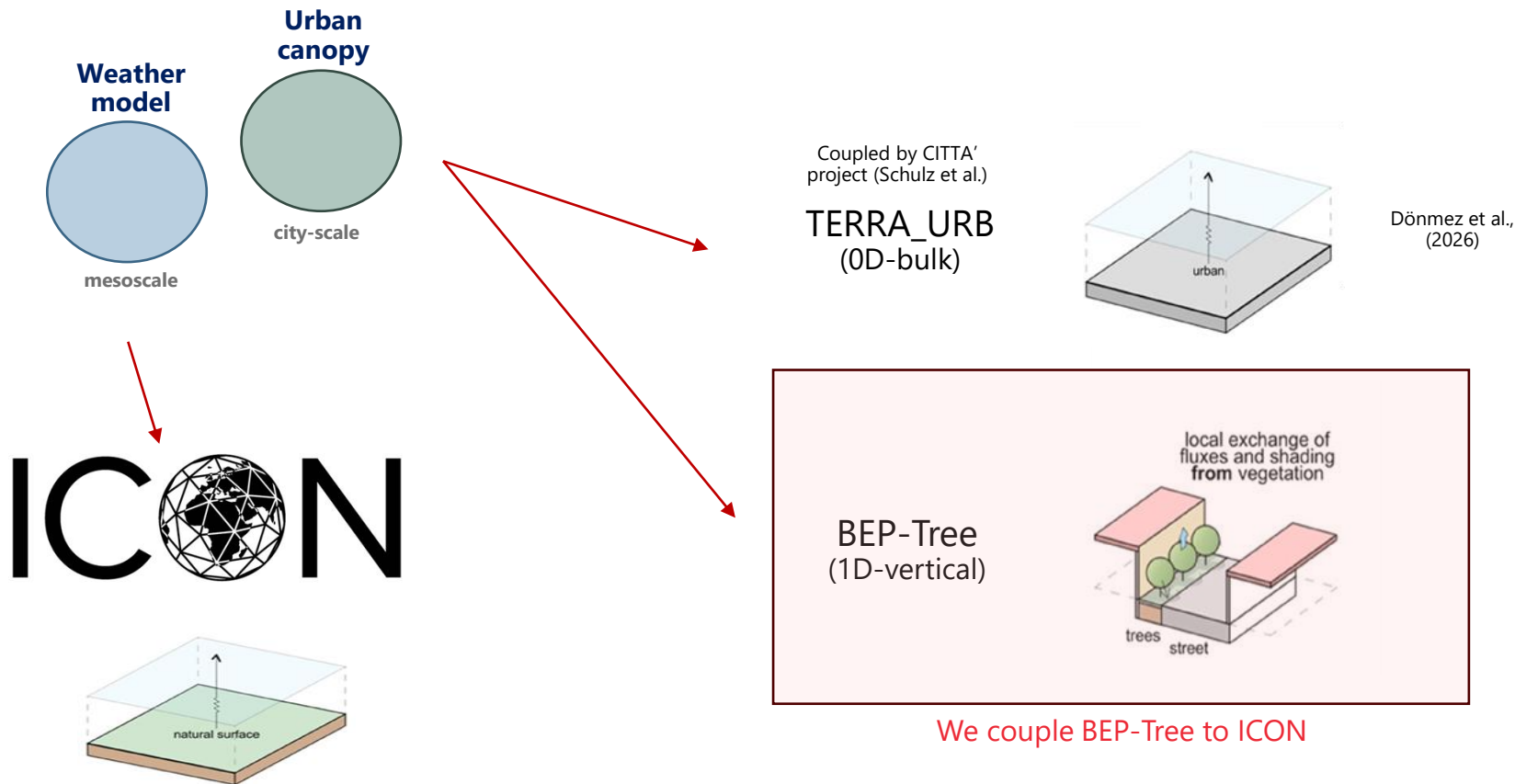
From regional model to building-resolved physics



Model choice depends on:

- What we want to study
- Over what spatial scale
- With how much physical detail
- At what computational cost

Coupled mesoscale and urban canopy models



BEP-Tree model

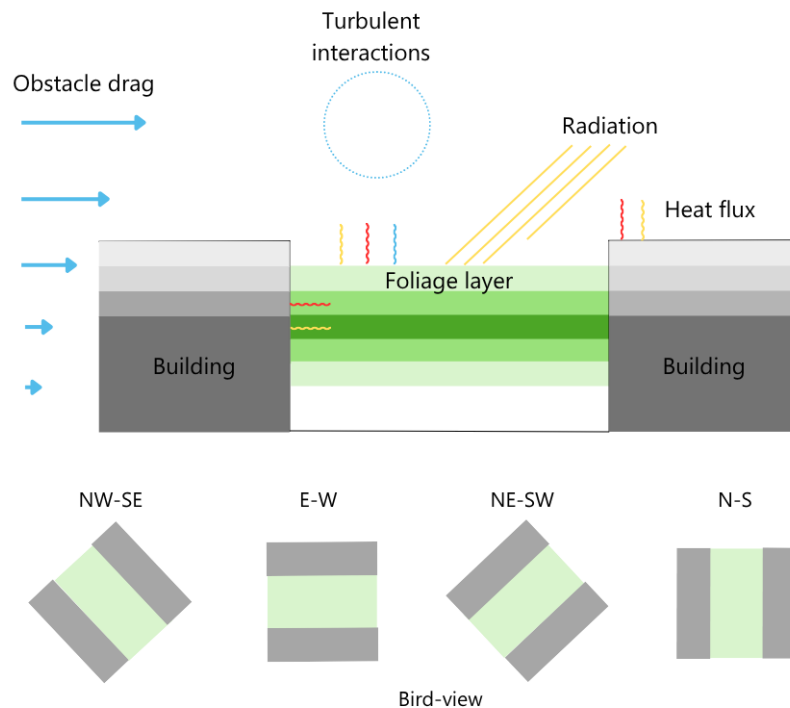


Multi-layer urban canyon with **trees**

- Radiative fluxes
- Heat fluxes (H/LE)
- Obstacle drag on flow
- Turbulent interactions

Urban effect calculated at **multiple** street orientations

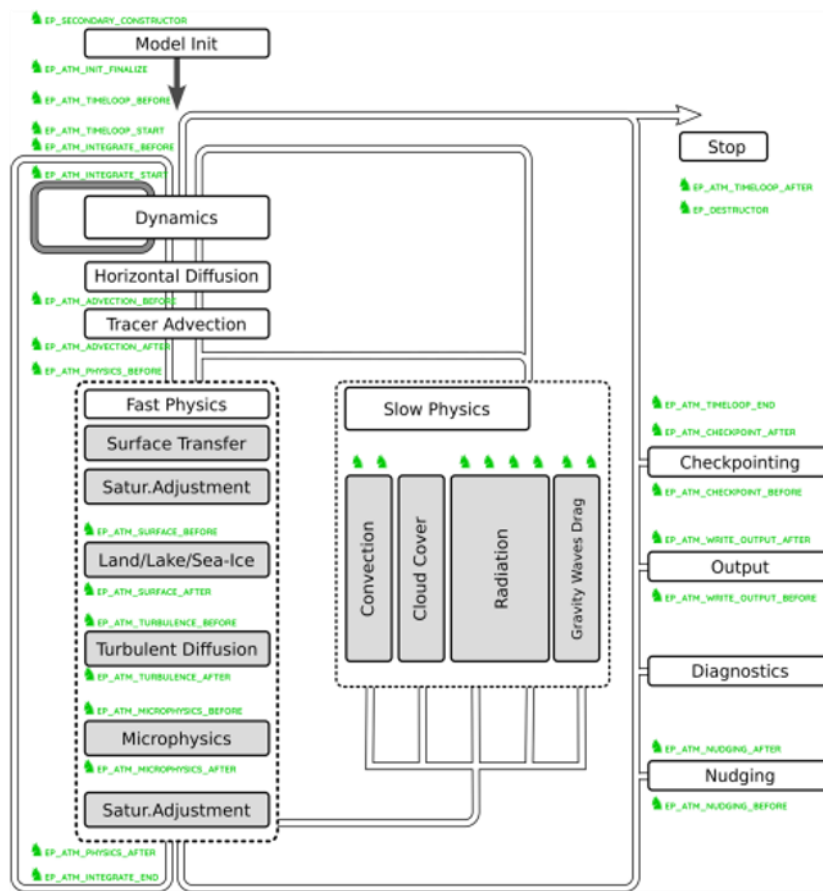
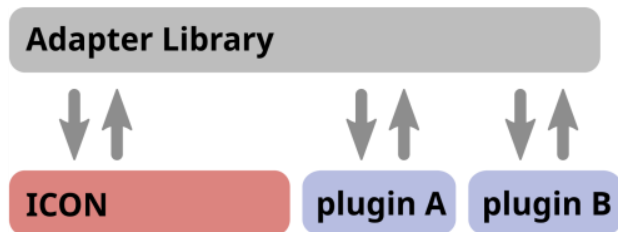
Physical processes in BEP-Tree



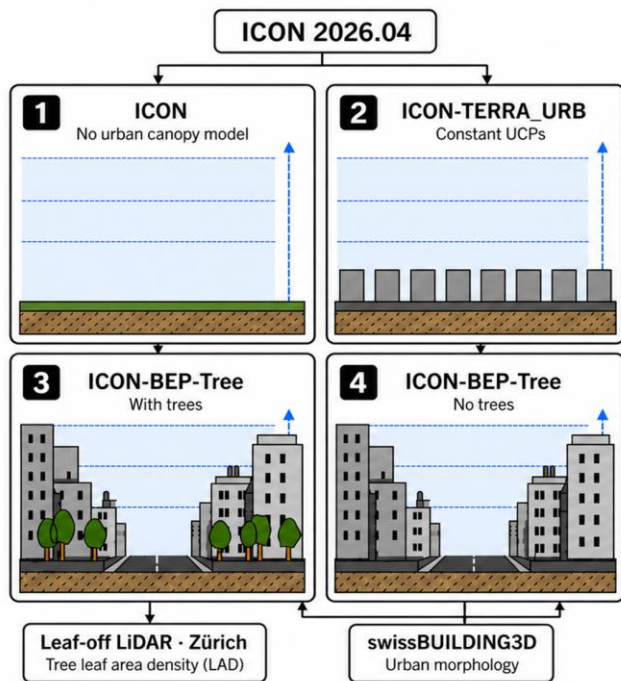
Coupling idea via ComIn



- **ComIn** connects external plugins to ICON and provides access to its data at pre-defined registration points.
- No change in ICON source code - maintainable



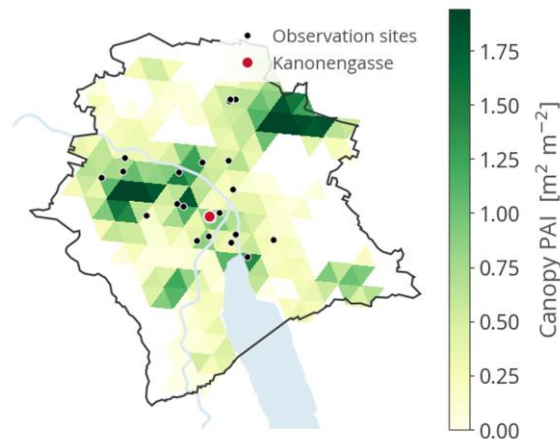
Simulating heatwave of summer 2026 over Zürich



Forced with **MCH ICON-1** over Zürich

500 m horizontal resolution

Simulation period: **June 2026**; with heatwave period defined as **20-27 June**



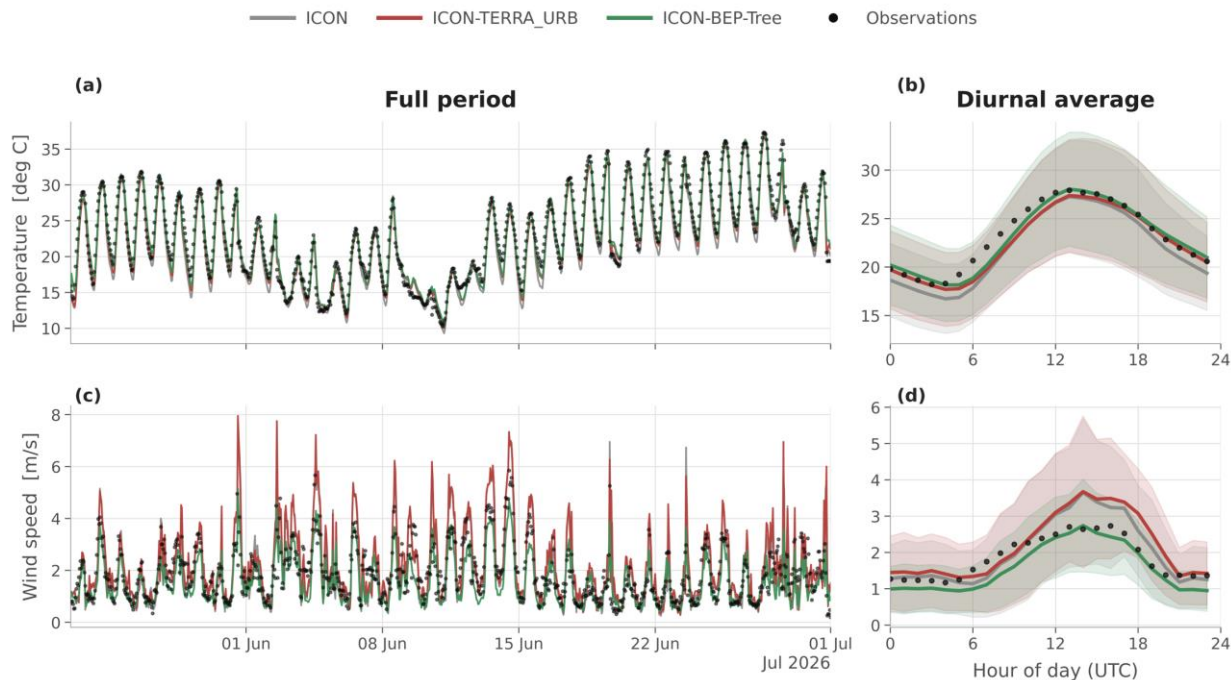
Observation locations, and selected analysis point for demonstration (Kanonengasse).

Model performance assesment



- All experiments agree well with observations
- Urban models improve nighttime warming in ICON
- ICON BEP-Tree improves daytime air temperatures
- New model also captures daytime wind reduction by urban drag

Site-mean temperature and wind speed



Should you use ICON BEP-Tree



Advantages

- ✓ Explicit building–tree–atmosphere interactions on the vertical
- ✓ Subgrid assessment of human thermal comfort via MRT and UTCI
- ✓ Flexible building-morphology and street-tree scenarios
- ✓ Better heatwave agreement than ICON and ICON TERRA-URB (June 2026)

Limitations

- ✗ Can take up to twice the runtime of standard ICON (less with low-frequency call)
- ✗ Coupling constrained by ComIn variable and hook access
- ✗ Albedo feedback not yet coupled
- ✗ Building-induced TKE dissipation not explicitly represented

Investigating the effect of a dedicated scheme for urban areas (TERRA_URB) in a kilometre-scale ICON forecasting configuration

Yann von der Weid – Master's Thesis

Supervised by: Dr. Christian R. Steger / Prof. Dr. Oliver Fuhrer

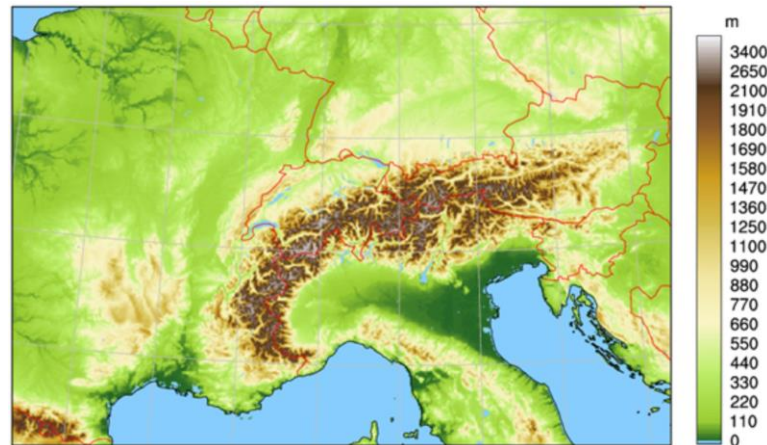
28th COSMO General Meeting

15.09.2026



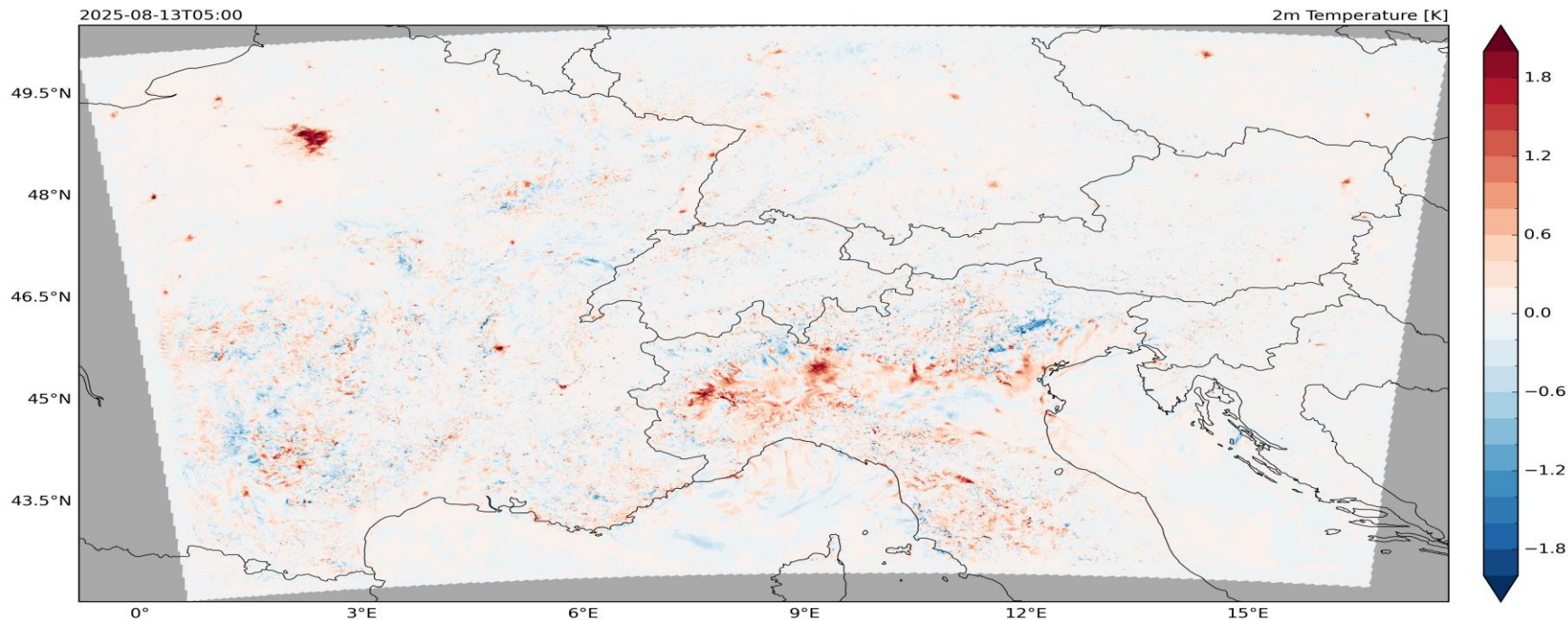
ICON Model Configuration

- 1 km resolution (also 500 m)
- Deterministic forecasts
- 48h lead time
- Verification 24-48 h (spin-up)
- Verification with default MCH stations & urban station selection
- Domain: Alps
- Rest according to standard operational MCH configuration

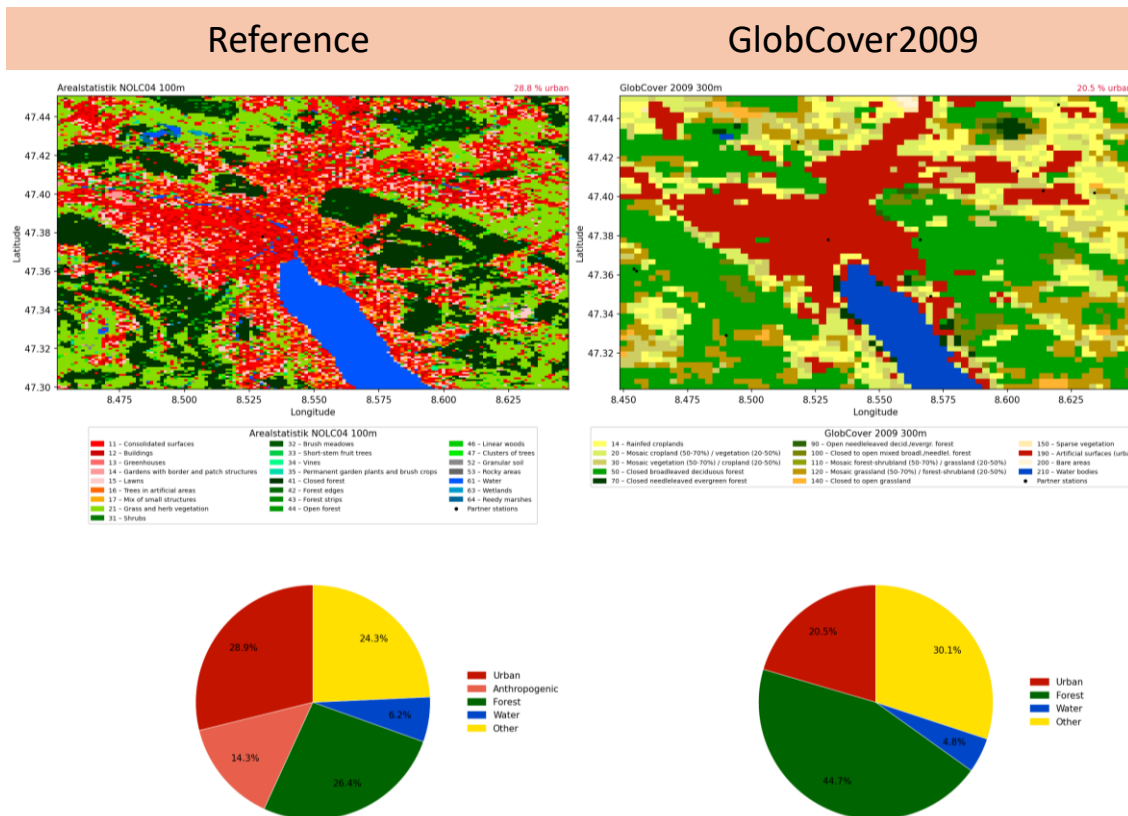


ICON MCH Domain

Difference TUT-TUF

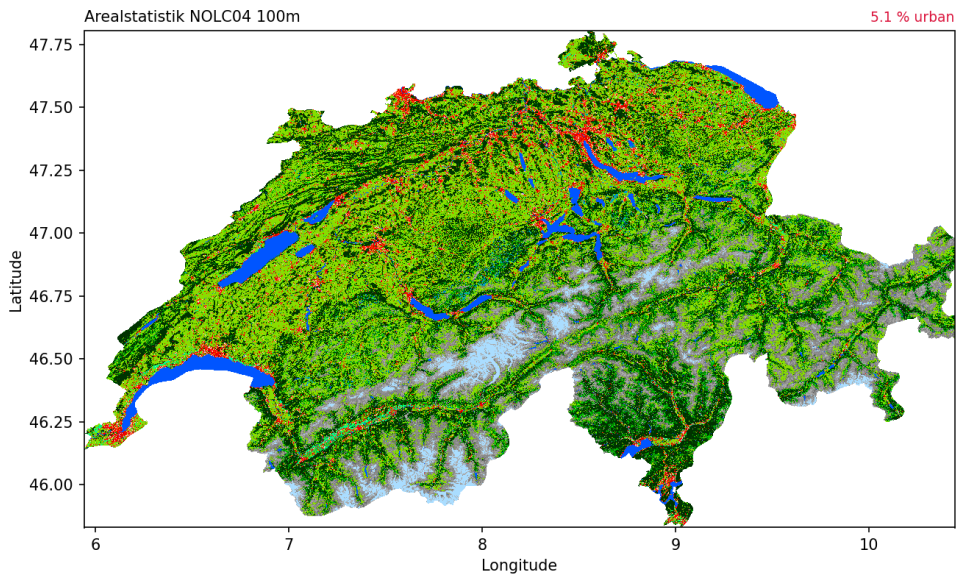


Land-Cover Comparison Reference Zürich

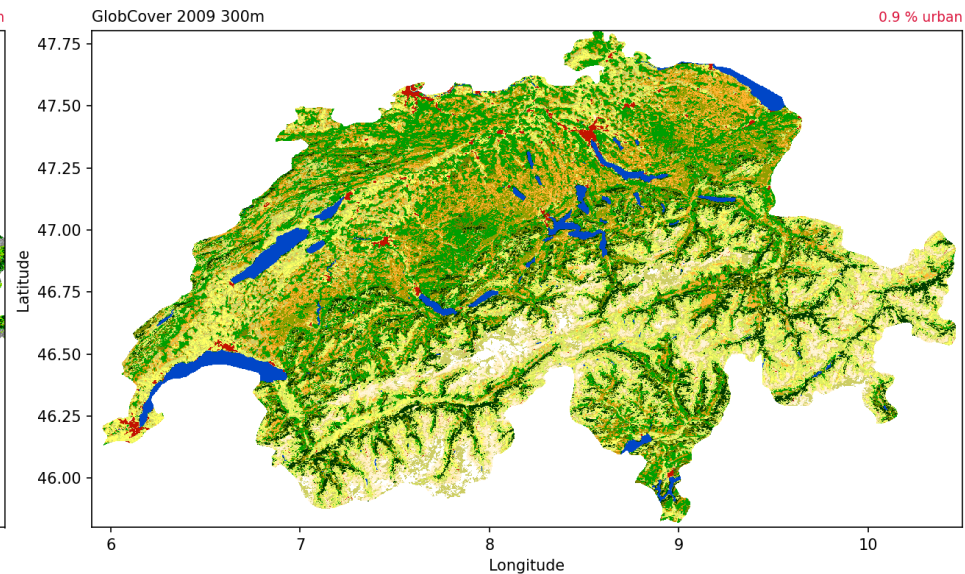


Land-Cover Datasets Comparison

Reference

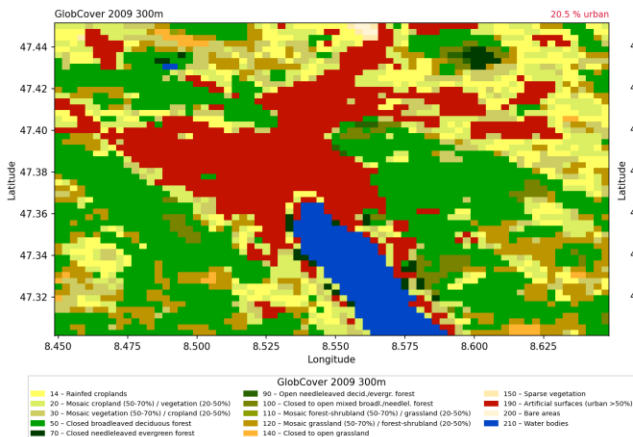


GlobCover2009

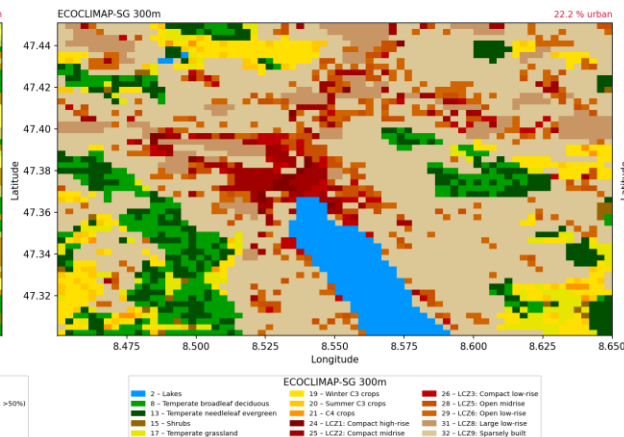


Combining GlobCover2009 & ECO-SG-ML

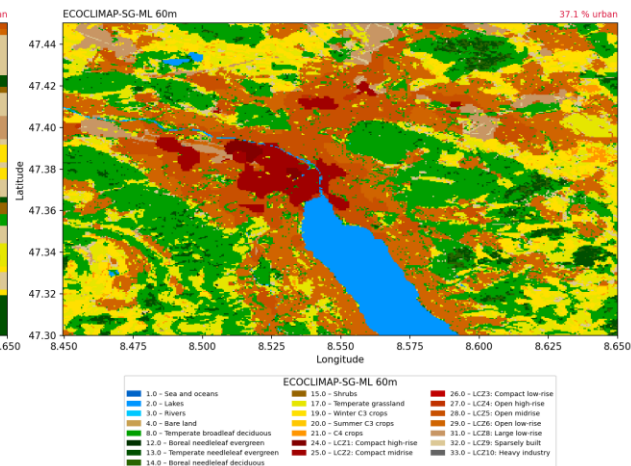
GlobCover2009



ECO-SG

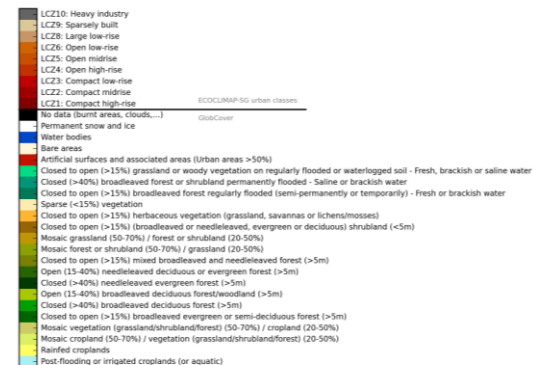


ECO-SG-ML

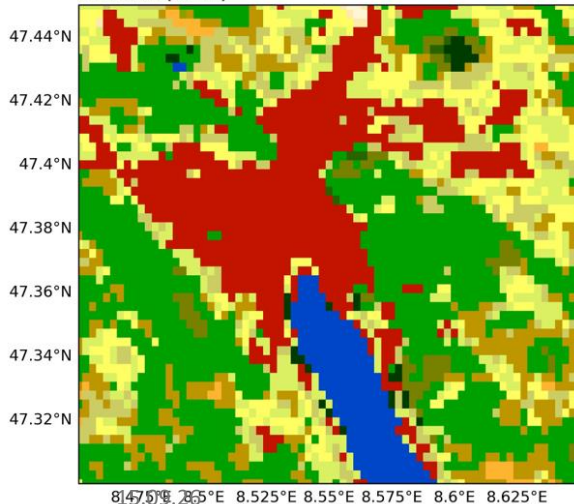


- Collapse GlobCover2009 to primary labels
- Find for every ECO-SG-ML 60 m pixel closest GlobCover pixel with same primary label and use the secondary GlobCover label for this pixel
- Urban areas: Keep ECOCLIMAP LCZ (variable classes)

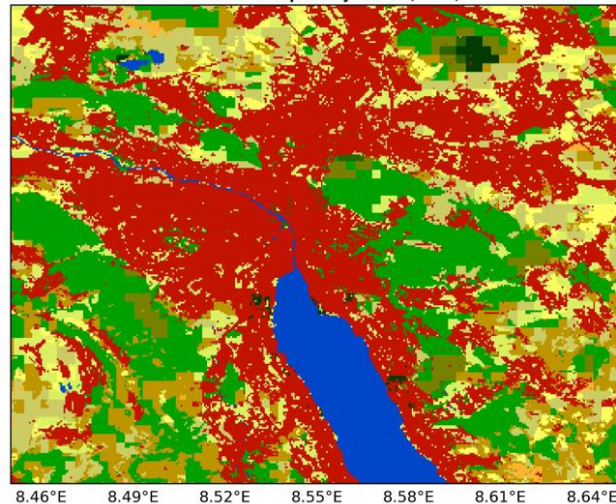
Globcover+ECO (60m)



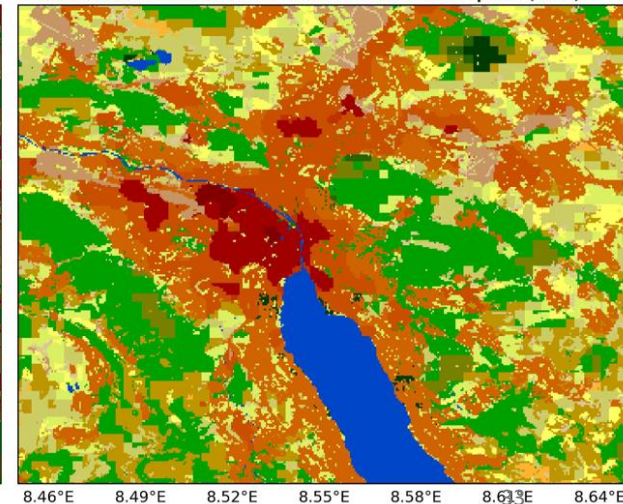
GlobCover (300 m)



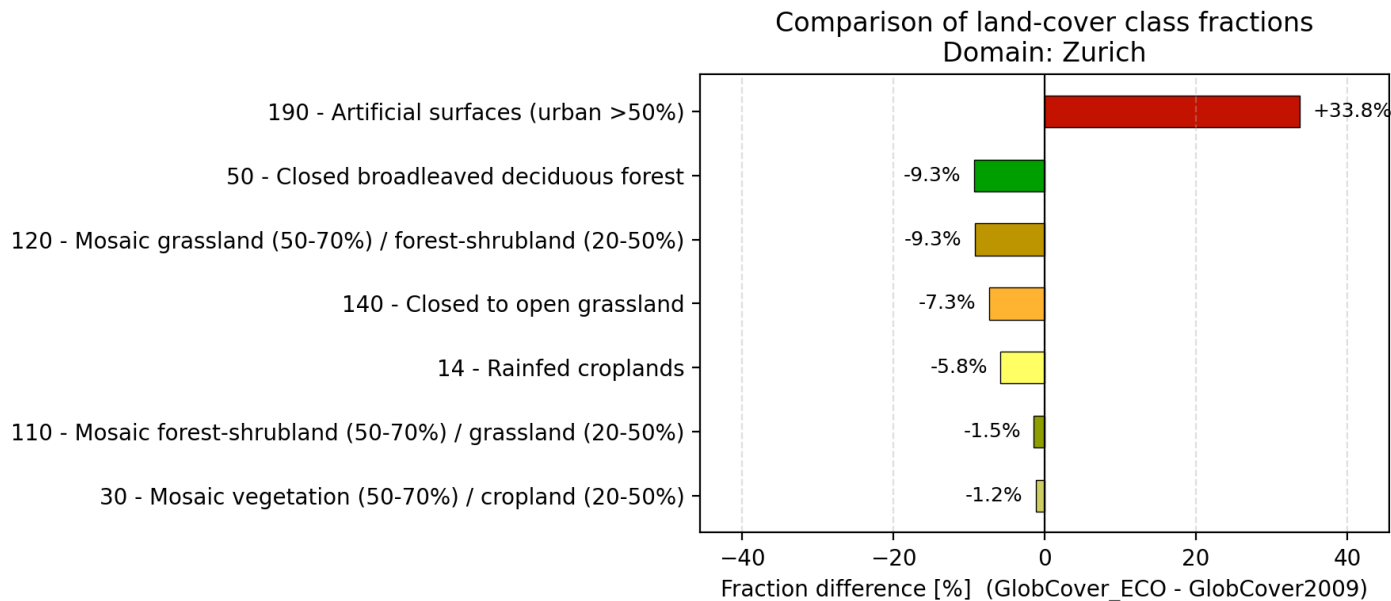
GlobCover with ECOCLIMAP-SG-ML primary labels (60 m)



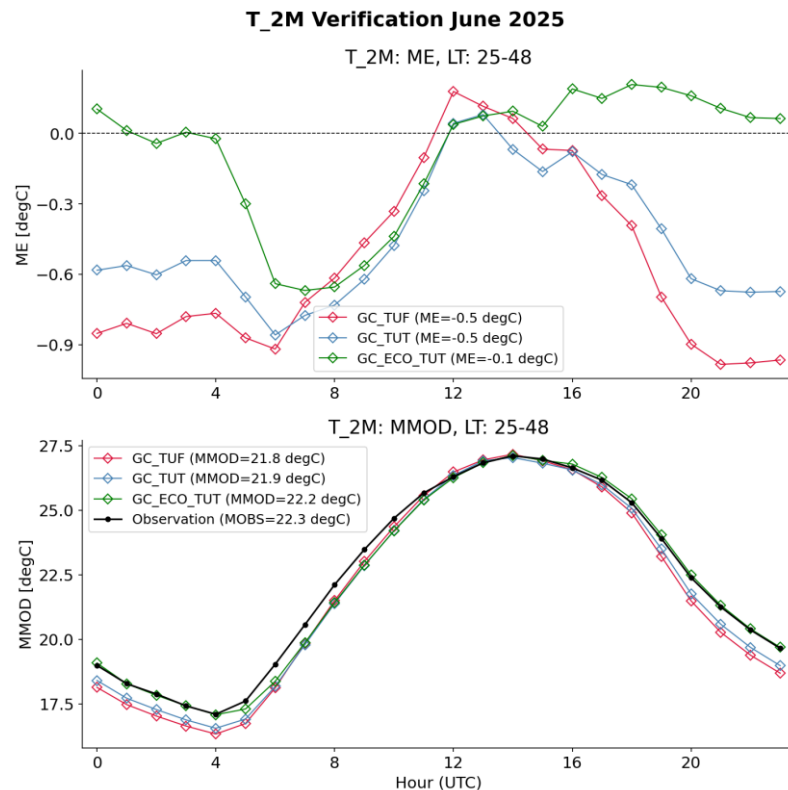
ECOCLIMAP-SG urban subclasses within GlobCover urban pixels (60 m)



Land-Cover classes comparison



Verification with urban Station Data



Inter - comparison of **ICON TERRA_URB** and **WRF** **BEP+BEM** for Urban Heatwave Events over Bologna City

A collaborative work between the University of Bologna and ARPAE Emilia-Romagna



Nagaraju Gaddam*



Ludovico Mattavelli



Dr. Thomas Gastaldo



Dr. Carlo Cintolesi



Dr. Jan-Peter Schulz



Dr. Andrea Zonato



Dr. Paolo Ruggeri



Dr. Chiara Marsigli



Prof. Silvana di Sabatino

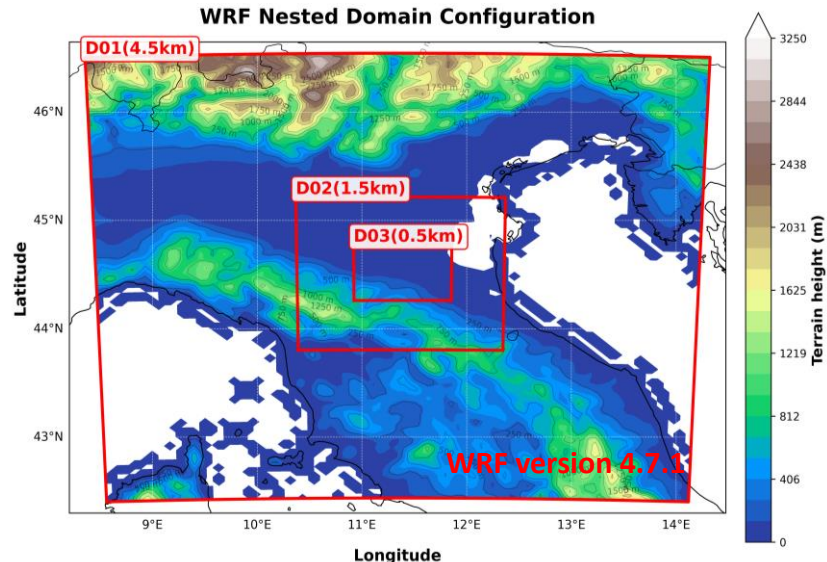


*PhD Student,
Future earth, climate change and societal challenges (40th cycle),
Department of Physics and Astronomy, UNIBO

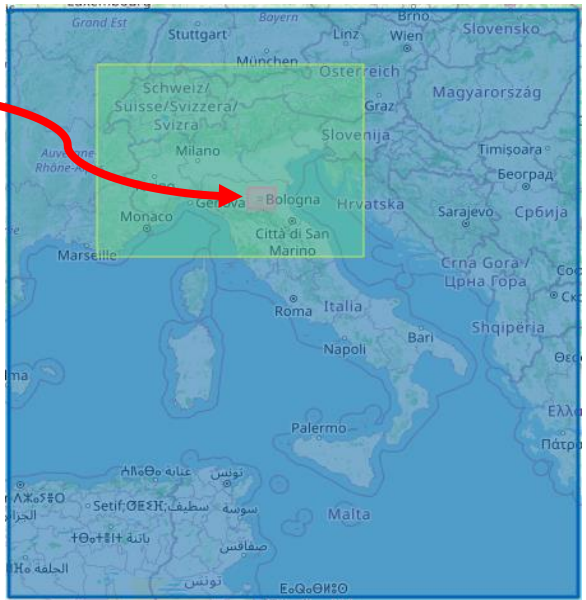
Outline

1. Motivation
2. Study Area & Case Studies
3. WRF and ICON Model Configurations
4. WRF BEPBEM and ICON TERRA URB Schemes
5. Observational Data & Evaluation
6. Results:
 - Temperature and radiosonde validation
 - Wind speed
 - Relative Humidity
7. Conclusions and way forward

WRF & ICON Model Configurations



ICON (0.5km)



Physics parameterization scheme.

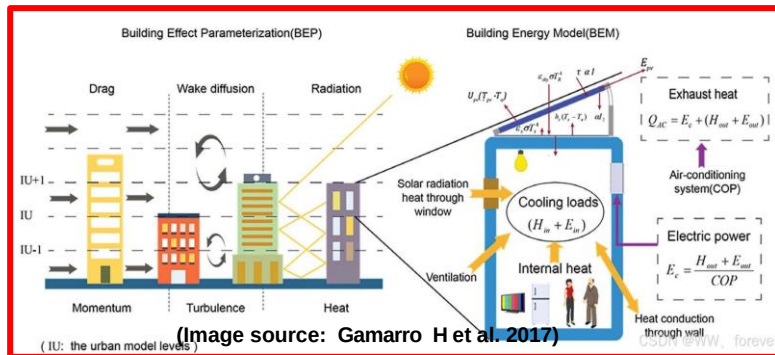
Planetary Boundary Layer	Mellor-Yamada-Janjic TKE scheme (MYJ)
Surface Layer Scheme	Monin-Obukhov (Janjic) scheme
Land Surface Model	Unified Noah land-surface model
Longwave radiation	RRTM (Mlawer et al.,1997)
Shortwave radiation	Dudhia scheme (Dudhia, 1989)
WPS LULC	100-m global CGLC-MODIS-LCZ
Vertical levels	51

Land Surface Model	TERRA
ICON LULC	300-m global GLOBCOVER 2009
Vertical levels	65

WRF & ICON Model Urban Schemes

WRF -BEPBEM (Martilli et al. (2002); Salamanca et al. (2010))

- Multi-layer urban canopy scheme: BEP coupled with the BEM
- BEP resolves momentum drag, turbulence (wake diffusion), and radiation trapping across multiple vertical levels within the urban canopy
- BEM simulates indoor building energy balance cooling/heating loads, internal heat gains, air-conditioning exhaust and feeds anthropogenic heat back into BEP

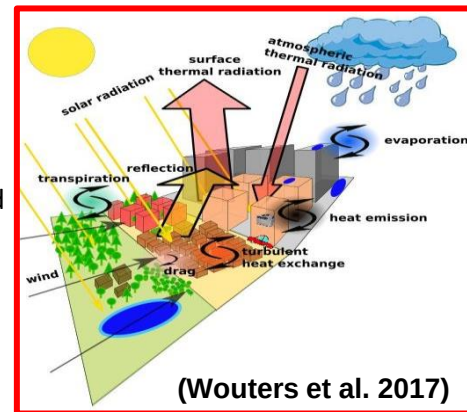


- Explicitly represents building height and street canyon geometry, enabling a fully 3D representation of heat and momentum exchange

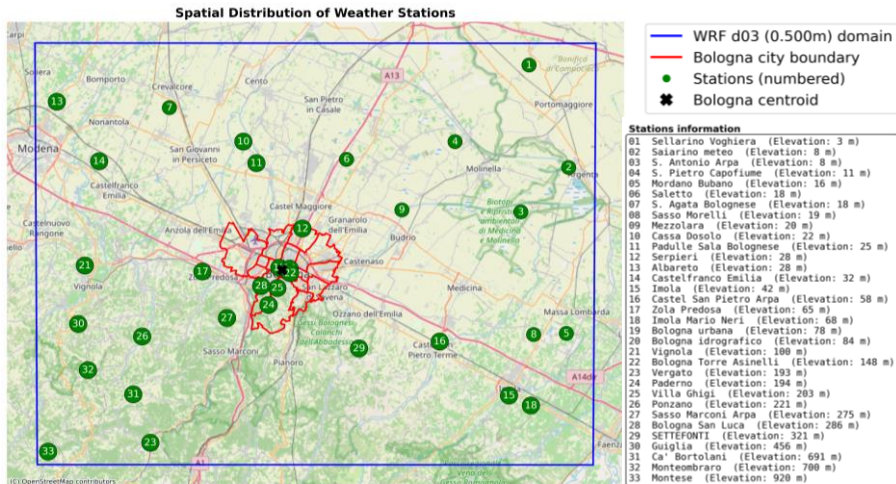
ICON - TERRA URB

- Single layer urban surface energy balance scheme, extending ICON's land surface model (TERRA) with bulk surface parameters
- Represents solar and thermal radiation exchange, turbulent heat exchange, anthropogenic heat emission, and reduced evapotranspiration relative to natural surfaces

2023: (Possega et al., 2026), 2015, (Zonato et al., 2020) simulated with WRF BEP+BEM and ICON TERRA_URB ERA5 boundary conditions, 12-hour spin-up



Observational Data and Evaluation



Stations classification:

Class	No of Stations	Criteria
Urban	3	Dense built-up city core
Suburban	9	Mixed built-up/vegetation, hillside periphery, small towns
Rural	16	Agricultural plain, <100 m elevation
Mountain	4	Apennine terrain, >450 m elevation

Observation data

Obtained the variables: Temperature, Wind speed, and Relative Humidity from the ARPAE station network for the 2023 August heatwave.

Model Data Post Processing

- Temperature, wind, and RH extracted at each station's nearest grid point
- 2 m temperature, RH2, UV10 are used where model elevation closely matches the station elevation; where elevation is mismatched, **vertical interpolation** is applied

Model Validation



**MAE (MEAN
ABSOLUTE
ERROR):
RANGES
FROM 0 TO ∞.**



**MBE (MEAN
BIAS ERROR):
RANGES
FROM -∞ TO ∞.**



**RMSE (ROOT
MEAN
SQUARE
ERROR):
RANGES
FROM 0 TO ∞.**



**CORRELATION
(R): RANGES
FROM -1 TO 1**

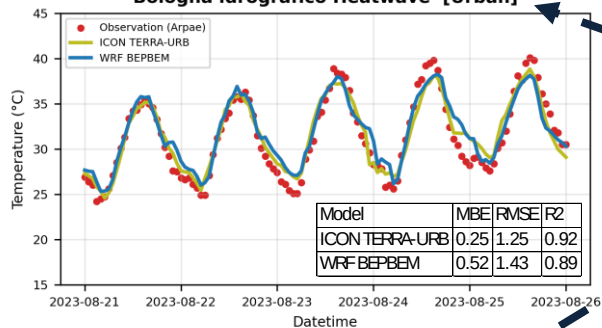


**R² (COEFFICIENT OF
DETERMINATION, PEARSON
): RANGES FROM 0 TO 1.**

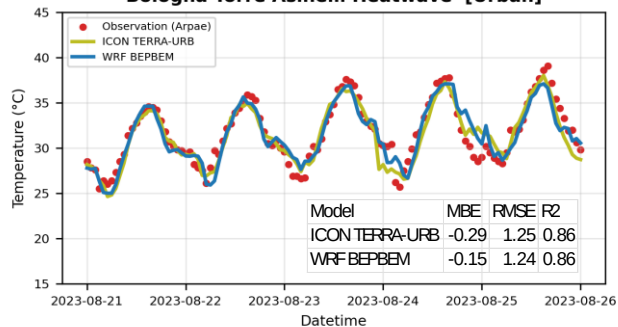
Bologna Urban Stations and Nearest Rural Stations

Urban Stations

Bologna idrografico Heatwave [Urban]

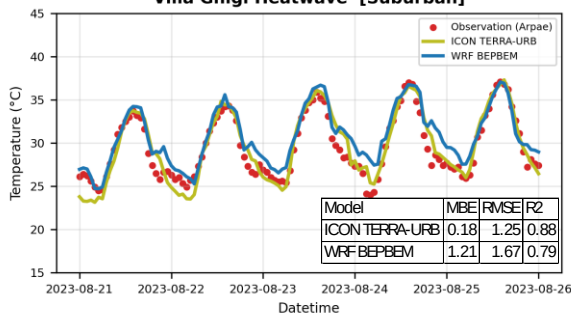


Bologna Torre Asinelli Heatwave [Urban]



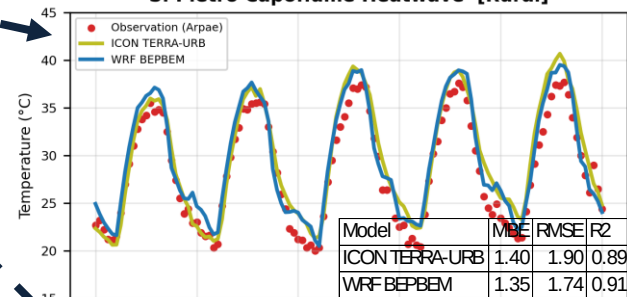
SubUrban Station

Villa Ghigi Heatwave [Suburban]

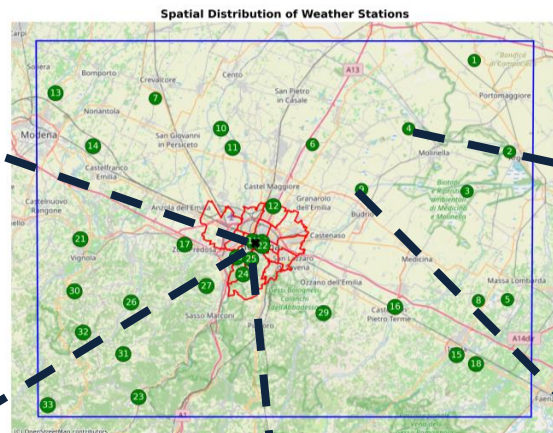
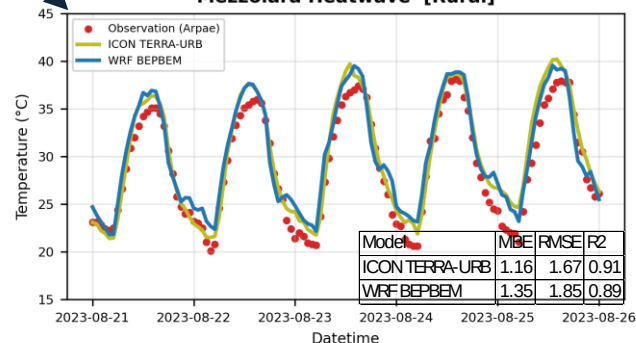


Rural Stations

S. Pietro Capofiume Heatwave [Rural]



Mezzolara Heatwave [Rural]



Conclusions of the validation:

- **Urban scheme sensitivity:** Both BEPBEM (WRF) and TERRA_URB (ICON) show their largest effect on bias at Urban stations, but TERRA_URB's effect is larger and follows a clear urban-to-rural gradient. At the same time, BEPBEM's is smaller and more uniform across all stations.
- WRF urban scheme overestimates wind speed and underestimates relative humidity across all stations, whereas ICON (TERRA_URB) has a limited effect on wind speed and reproduces relative humidity well.
- **Temperature:** ICON TERRA_URB outperforms WRF BEP+BEM in both bias and RMSE across Urban, Suburban, and Rural stations, with the two models converging at Mountain stations.
- **Wind speed:** Both models struggle to reproduce observed wind speed; R^2 is negative at nearly every station for both models, indicating a shared limitation independent of the urban canopy scheme.
- **Relative humidity:** Both models underestimate humidity, but WRF BEPBEM's bias is much larger than ICON TERRA_URB's across all stations, with correspondingly higher RMSE.
- **2015 heatwave:** These same patterns held up in the second heatwave case too so the results aren't a one-off, they're consistent across events.

The impact of ParFlow's 3D subsurface hydrodynamics on ICON' atmosphere

M. Waldmann, J. Weinkaemmerer, R. Schnur,
K. Georgen, S. Kollet, L. Schlemmer

Presented by
Jan-Peter Schulz

ICON-ParFlow coupling & simulation setup

Technical details of the coupling:

- The coupling was implemented by Jan Weinkaemmerer (FZJ) in the WarmWorld project¹
- ParFlow² solves the 3D Richards equation for variably saturated subsurface water flow and a kinematic wave equation for surface run-off
- ParFlow is coupled to ICON-LAND (JSBACH) via YAC³
- The exchanged variables are the net water flux ($P - ET$) calculated by ICON-LAND and the soil water content (SWC) calculated by ParFlow
- Spatial interpolation of the exchanged fields (horizontally and vertically):
 - ParFlow's and ICON's horizontal mesh differ (Cartesian vs. triangular mesh)
 - ParFlow's 15 soil layers cover a depth of 60m (thicknesses range 2cm - 18m)
 - ICON-LAND's 5 soil layers cover a depth of 10m (thicknesses range 6cm - 5m)
- Temporal interpolation of the exchanged fields
 - ICON-LAND sends the temporally averaged net water flux ($P - ET$) to ParFlow
 - ParFlow sends instantaneous soil water content to update ICON-LAND's hydrology state in timesteps when it is active
 - ICON-LAND uses its own hydrology scheme in timesteps when ParFlow is inactive

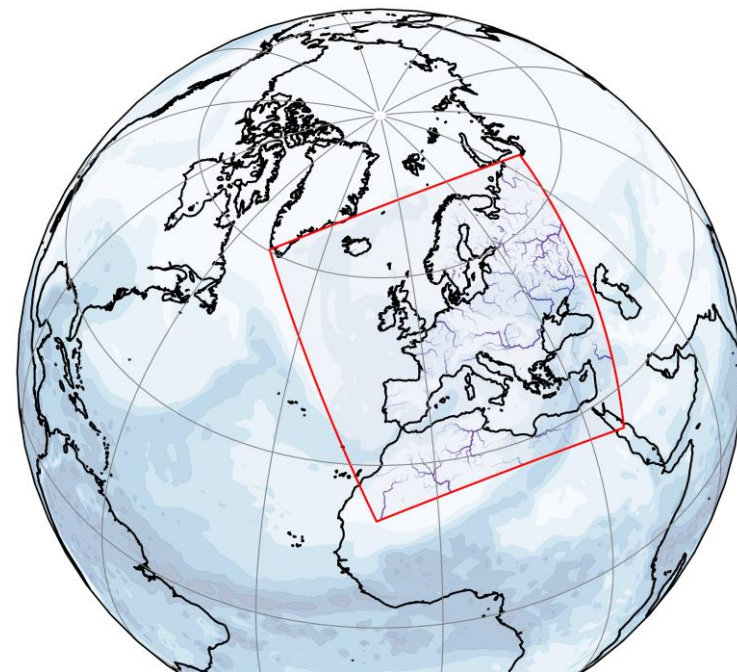


Fig. 1: Computational domain of the Limited Area Mode (LAM) simulation¹

¹ Weinkaemmerer et al.:
10.22541/essoar.174241644.47338830/v1

² <https://www.parflow.org>

³ Hanke et al.: 10.5194/gmd-9-2755-2016

Influence of the orography

Cell classification:

- Gravitational forces drag water downhill into valleys and river corridors
- Cells are categorized by the Topographic Position Index (TPI)

$$TPI_i = z_i - \frac{1}{N} \sum_N z_j$$

- The N neighboring cells j are all cells sharing at least one vertex with cell i
- Mountain ridges and valleys are defined as the **5th** and **95th** percentile of the TPI values
- Steep valleys (**>75th** percentile) and flat mountain ridges (**<25th** percentile) are moved to flat terrain/hillslope cells
- Hillslope cells are a subclass of the remaining cells with a hillslope of at least **2%**
- Flat terrain cells are all other cells
- Glaciers, lakes, and sea cell are excluded

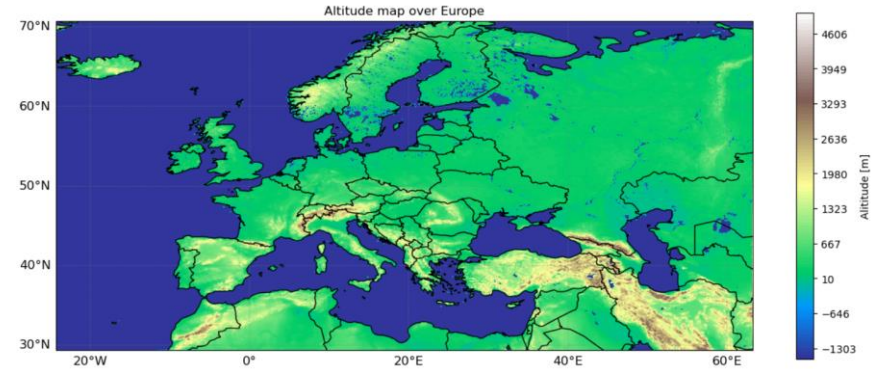


Fig. 3: Surface elevation over Europe

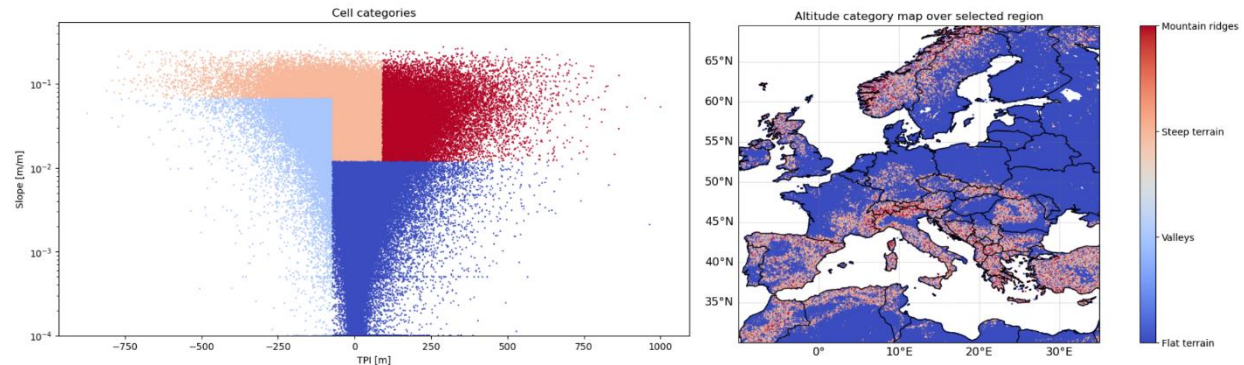


Fig. 4: Cell categorization plotted over slope and TPI (l.) and on the map of Europe (r.)

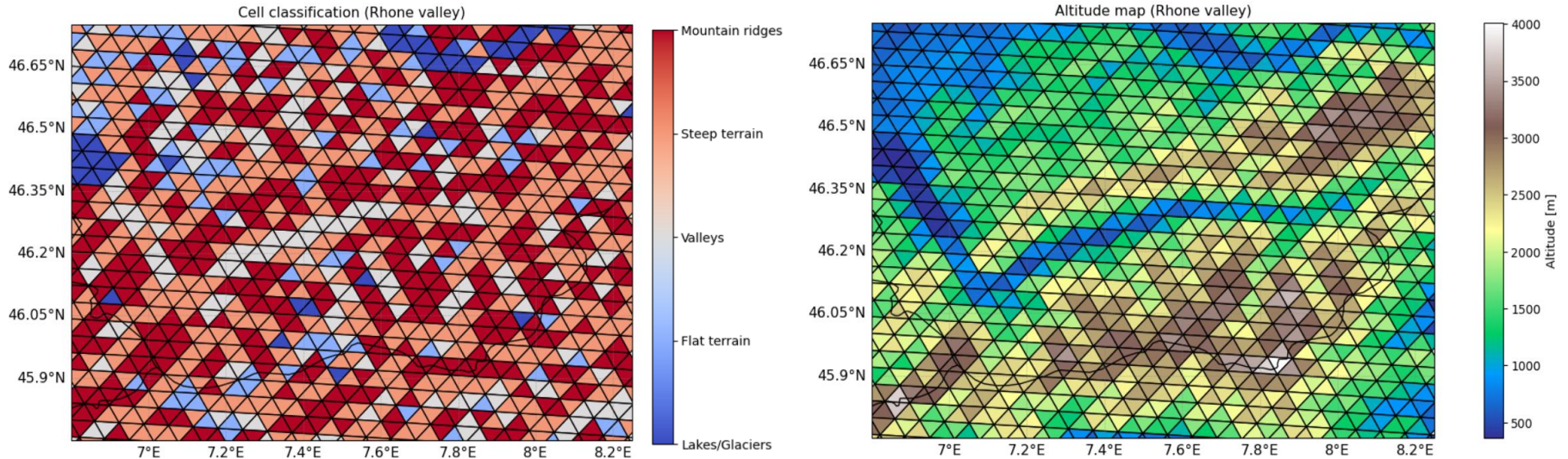


Fig. 5: Cell categorization (l.) and elevation (r.) plotted for the Rhone valley in Switzerland

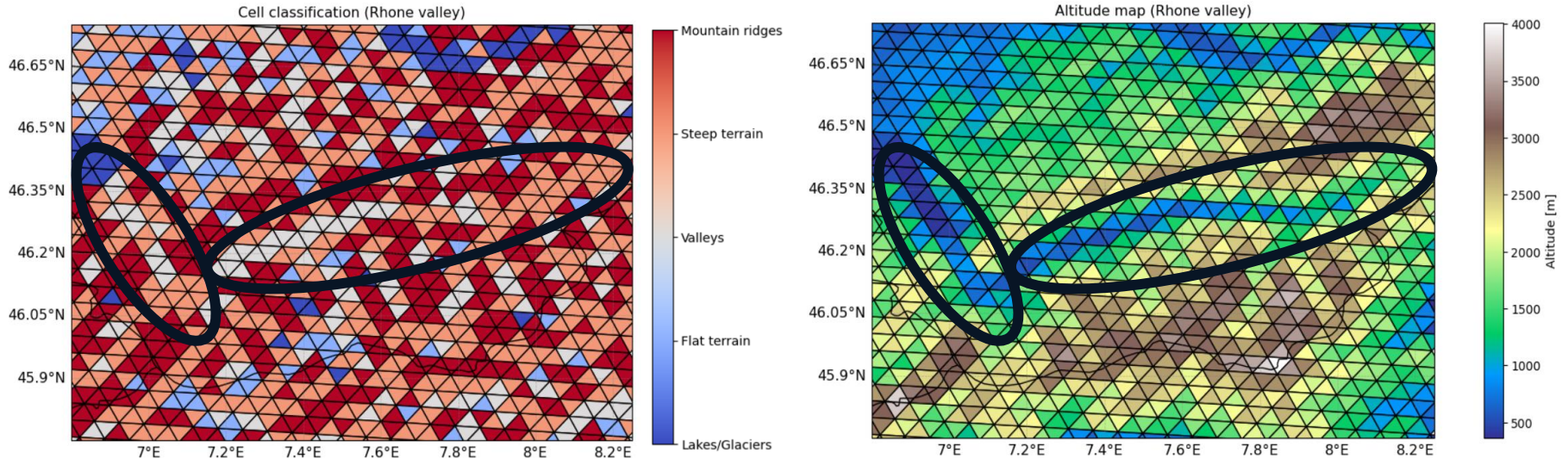


Fig. 5: Cell categorization (l.) and elevation (r.) plotted for the Rhone valley in Switzerland

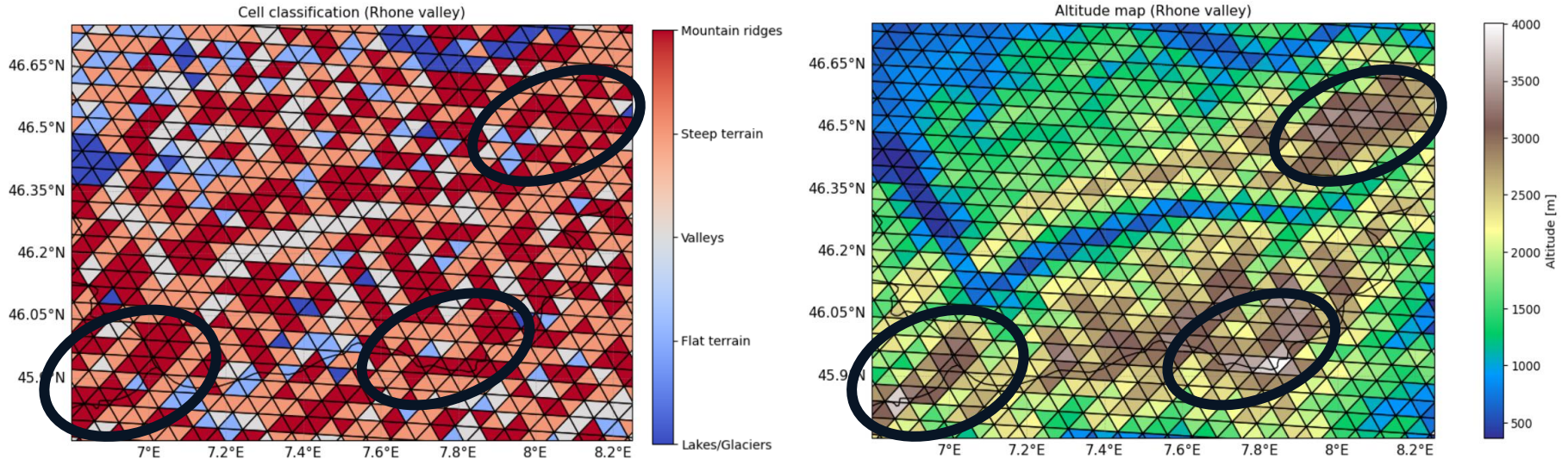


Fig. 5: Cell categorization (l.) and elevation (r.) plotted for the Rhone valley in Switzerland

Influence on the subsurface hydrology & near surface diagnostics

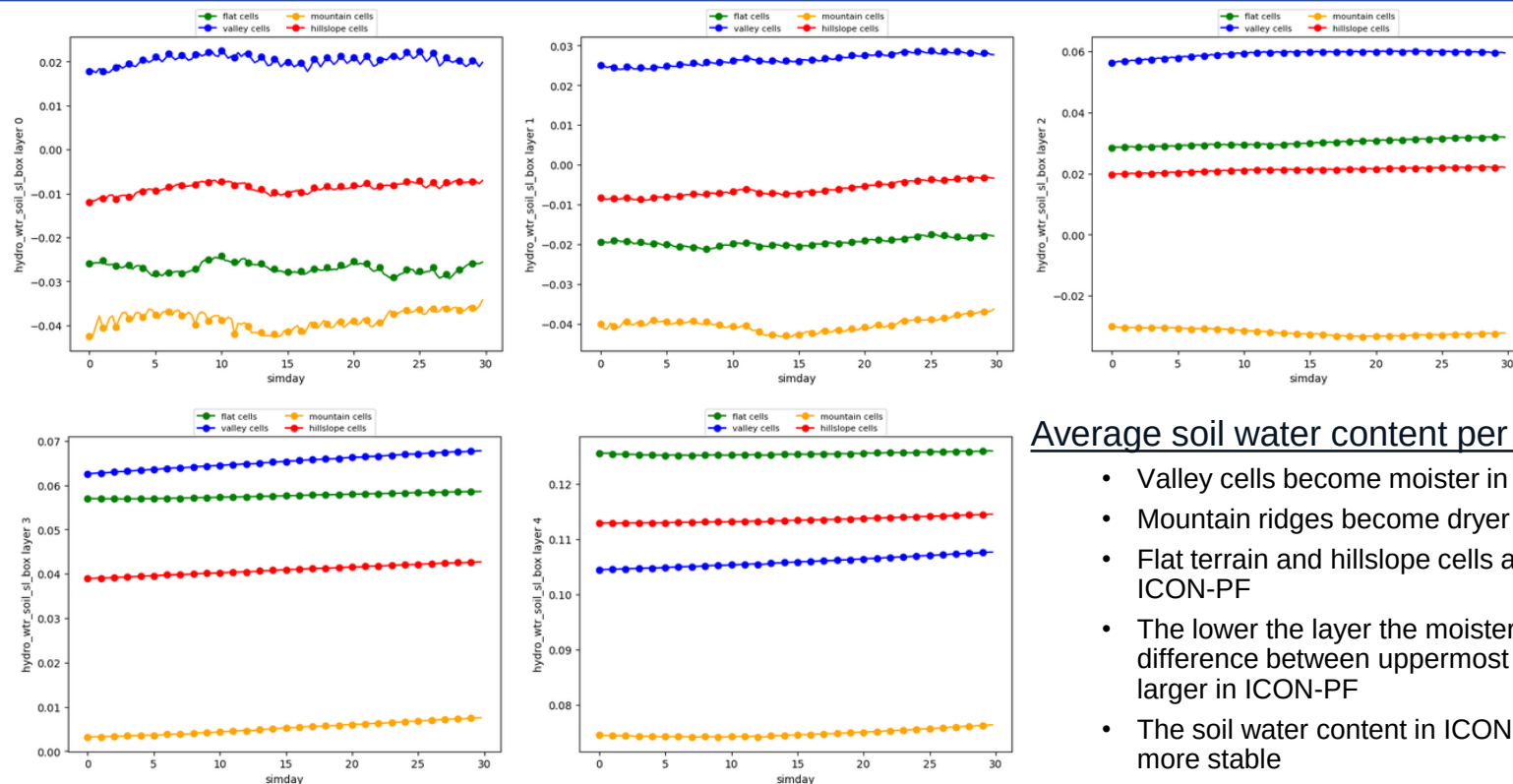
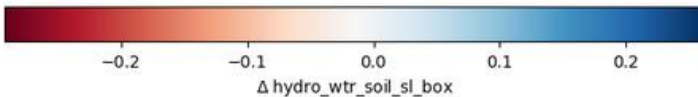
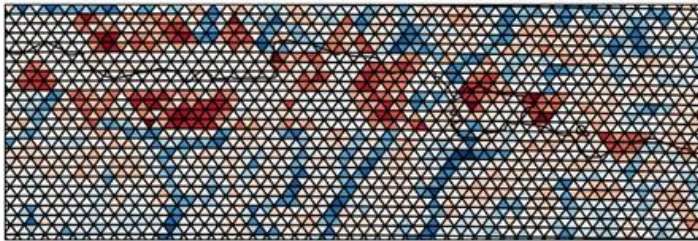
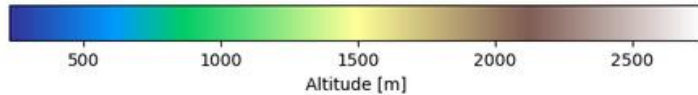
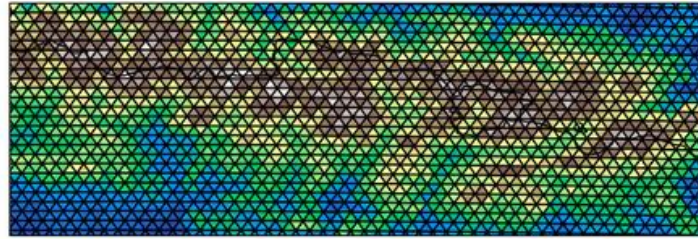


Fig. 7: Difference in vol. soil water content for all 5 layers of JSBACH (ICON-PF– ICON-Ref)

Average soil water content per category:

- Valley cells become moister in ICON-PF
- Mountain ridges become dryer in ICON-PF
- Flat terrain and hillslope cells are slightly dryer in ICON-PF
- The lower the layer the moister the soil, but the difference between uppermost and lowermost layer is larger in ICON-PF
- The soil water content in ICON-PF's deep layer is more stable



Soil water distribution over Pyrenees:

- The soil water content in the uppermost soil layer of valleys in the Pyrenees is larger in ICON-PF
- The larger soil water content increases evapotranspiration in the valleys
- Due to evapotranspiration, the energy partitioning in the valleys changes
 - Latent heat fluxes increase
 - Sensible heat fluxes decrease
- As a consequence, the near surface temperature decreases and the near surface humidity increases

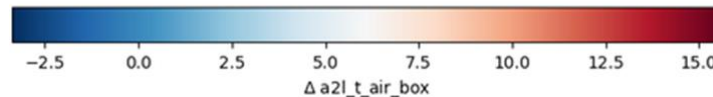
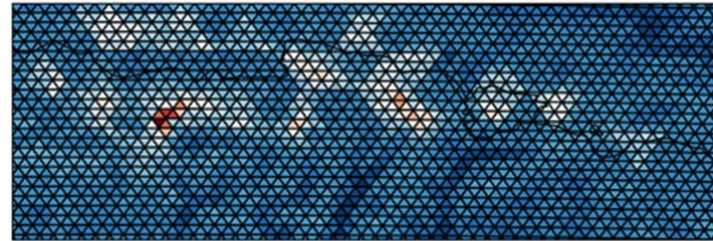
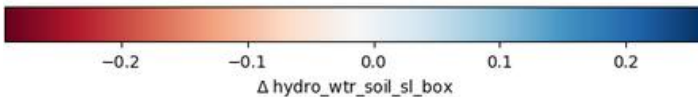
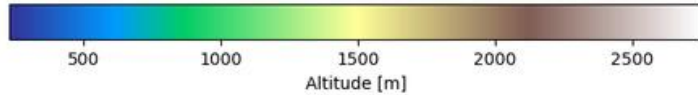
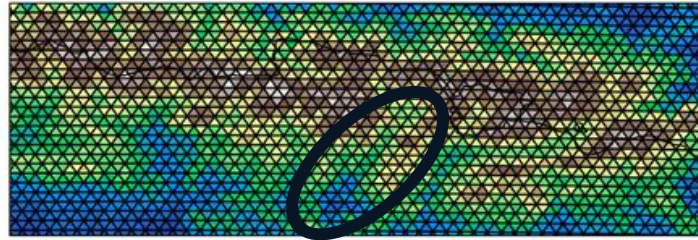


Fig. 11: Surface elevation (u.), soil water content difference in the upper layer (b.l.) and 2m temperature difference (b.r.) are shown in the Pyrenees for each mesh triangle



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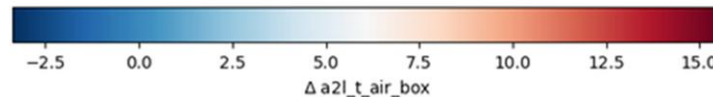
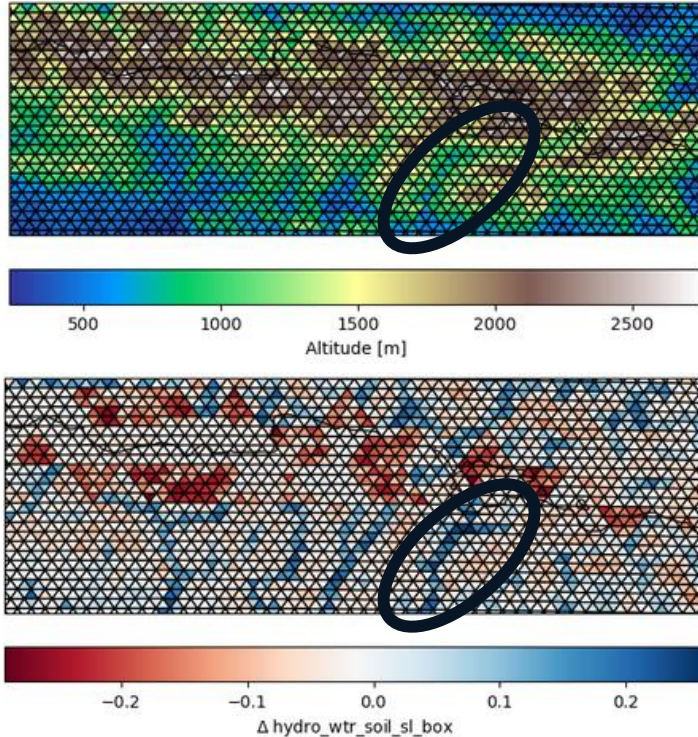


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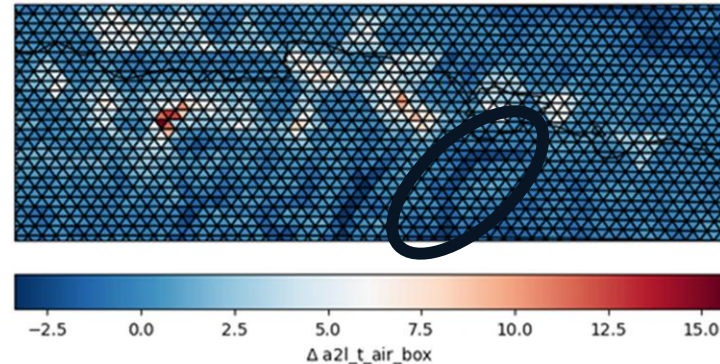


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Summary:

- Using ParFlow heterogenizes the distribution of soil water content due to lateral water transport (subsurface + runoff)
 - The soil in valley cells tend to become moister
 - The soil in mountain ridge cells tend to become dryer
 - In flat terrain, the differences are smaller but still visible
 - When using ParFlow, rivers build naturally as a consequence of the local orography
- The differences in soil water content alter the surface fluxes
 - The evapotranspiration in valley cells increases, especially in dry regions as the Pyrenees
 - Mountain ridge cells show a shift of the energy partitioning from latent heat flux towards sensible heat flux
- The surface fluxes influence the state of the near-surface diagnostics
 - The 2m temperature and humidity in valleys of the Pyrenees is reduced if the soil moister increases due to lateral water transport by ParFlow
- ParFlow's influence on further atmospheric variables requires further investigation

ICON · EXTPAR · TERRA

Advances in ICON External Parameter Generation and Land-Surface Modelling

High-Resolution Soil & Water-Body Processing · Operational Production with Zonda
Standalone TERRA Diagnostic Framework

J. Helmert, S. Brand, M. Stellio, J. Förstner, Ch. Steger, L. Schlemmer



Why this matters for ICON



1 High-res aggregation

Soil (250 m) and water-body (30 m) data → fractional fields on unstructured ICON grids without memory explosion.



2 Operational production

Migration of EXTPAR to Zonda + post-processing → consistent NetCDF & GRIB2 for 20+ grids.



3 TERRA diagnostics

Standalone test harness for isolated, reproducible testing of land-surface physics.

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Global high-resolution data → ICON fractions



Glo-30 Water-Body Mask

Global 30 m resolution

Grid size	648 000 × 1 296 000 (30m)
Pixels	~840 billion
Classes	0 = Land, 1 = Lake, 2 = River
Target	FR_LAND, FR_LAKE, FR_RIVER
ICON grid	R03B07 · ~2.95 M cells



SoilGrids / HiHydroSoil

Global 250 m soil properties

Source	SoilGrids / HiHydroSoil
Resolution	~250 m global
Variables	KSAT, texture, thermal...
Output	mean / min / max / var

Global HiRes Water-Body-Mask

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



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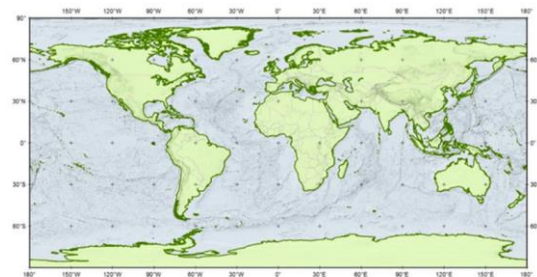
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Copernicus DEM – Global and European Digital Elevation Model

Digital Surface Model (DSM) provided in 3 different resolutions (90m, 30m, 10m) with varying geographical extent (EEA: European and GLO: global) and varying format (INSPIRE, DGED, DTED).

GLO-30 and GLO-90: worldwide coverage

GLO-30 offers global coverage at a resolution of 30 metres. GLO-90 offers global coverage at a resolution of 90 metres. Both datasets have a surface coverage of ~ 149 M km².



Land surface coverage within Copernicus DEM – GLO-30 & GLO-90

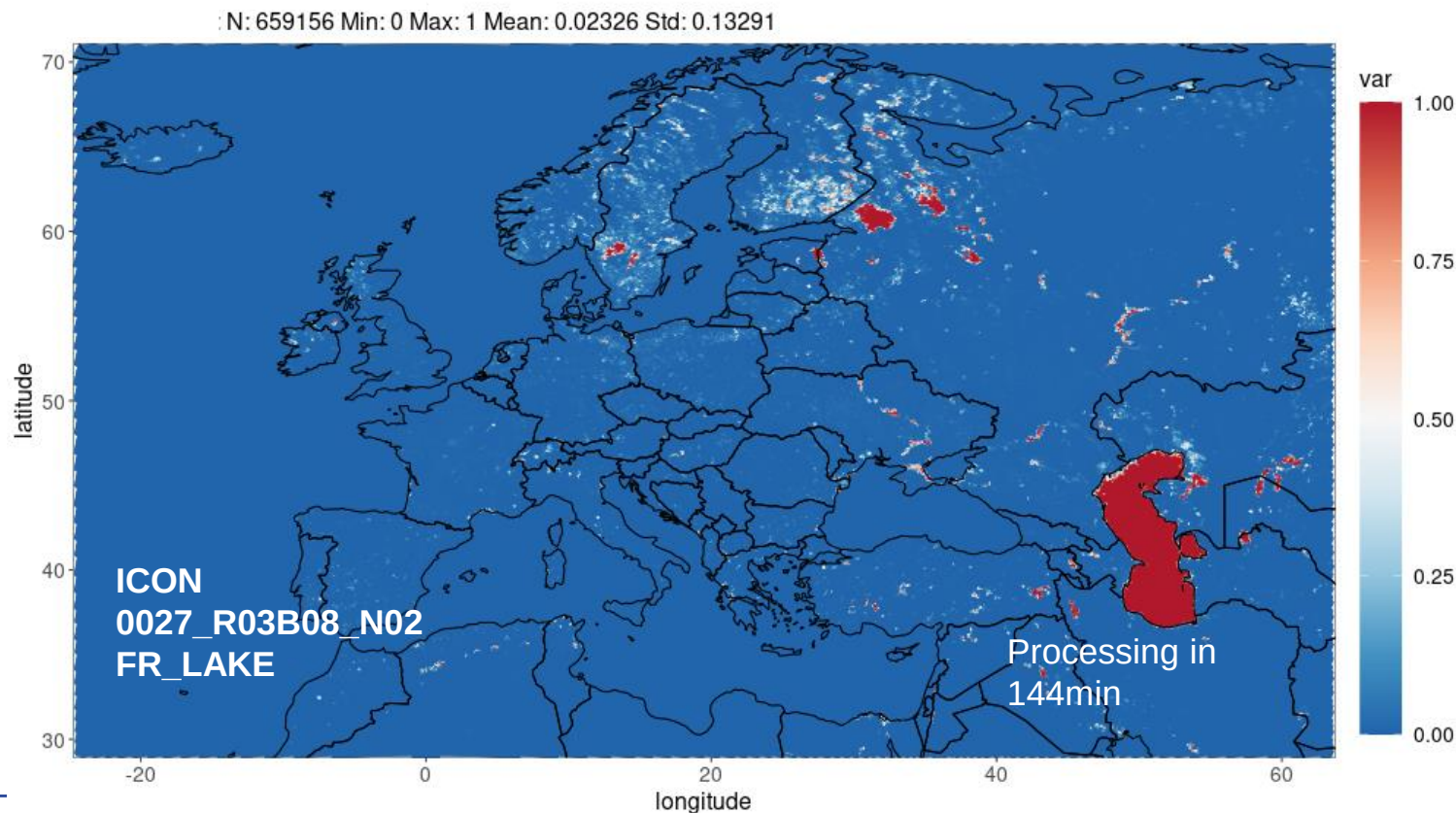
Copernicus DEM – Global and European Digital Elevation Model

The Copernicus DEM is a Digital Surface Model (DSM) that represents the surface of the Earth including buildings, infrastructure and vegetation. The Copernicus DEM is provided in 3 different instances: EEA-10, GLO-30 and GLO-90.



Global HiRes Water-Body-Mask

Deutscher Wetterdienst
Wetter und Klima aus einer Hand



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MOTIVATION: WHY ISOLATE TERRA?



Tight Coupling

TERRA is deeply embedded in the full ICON infrastructure (config, MPI, OpenACC, lookup tables).



Hard to Debug

Reproducing a single-column failure requires a complete model run and complex diagnostics.



Slow Iteration

Physics development and regression tests are slowed by the full model build and runtime cost.

SOLUTION ARCHITECTURE



Design Principle

Reuse pre-compiled ICON object files and module files where possible. Only the test driver is compiled locally. Dummy modules supply missing namelist parameters and physical constants that are normally set by the full model.

CONCLUSIONS & OUTLOOK



Feasible Isolation

TERRA can be extracted into a practical, single-column test harness without rewriting the physics.



Faster Development

Enables rapid iteration, regression tests and targeted debugging of soil, snow and flux processes.



Verification Tool

Provides a controlled environment for comparing numerical behaviour against full ICON runs.



Next Steps

Extend coverage to multi-layer snow cases, discuss to add to icon-tools or icon gitlab



Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

Federal Department of Home Affairs FDHA
Federal Office of Meteorology and Climatology MeteoSwiss



Almost ready to merge...

NIX in Modular TERRA

Nander Wever^{1,2}, Sascha Bellaire³, Michael Lehning^{1,4}, Jean-Marie Bettems²

Daniel Hupp², Lukas Jansing²

¹WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

²MeteoSwiss, Zurich, Switzerland

³Deutscher Wetterdienst (DWD)

⁴CRYOS, School of Architecture, Civil and Environmental Engineering, EPFL, Lausanne, Switzerland



Background



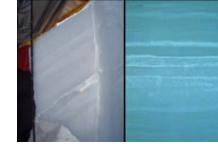
- Concerted effort from MeteoSwiss and the Swiss WSL Institute for Snow and Avalanche Research SLF (Nander Wever) and DWD (Sascha Bellaire) to improve the representation of snow processes by implementing NIX
- **End of 2024, we decided to integrate NIX inside Modular TERRA, and to integrate NIX inside JSBACH (fully coupled with mass and energy balance)**





NIX

- Multi-layer, physics-based snow cover model, based on the detailed SLF SNOWPACK model
- From Essery et al. (2012): "There is no clear link between model complexity and performance, **but the most consistent results come from configurations that have prognostic representations of snow density and albedo and that take some account of storage and refreezing of liquid water within the snow.**"



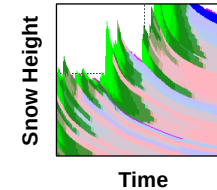
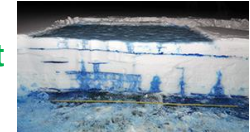
Layering (create/aggregate/split)

Heat Equation_(implicit) $\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}; \quad 0 \leq x \leq L; \quad t^3 \geq 0$



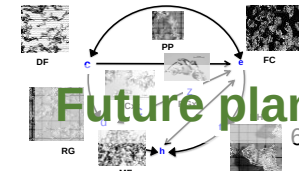
Phase Changes

Water transport



Settling

Snow microstructure



Future plans

69



General implementation concept TERRA + NIX

sfc_terra_main.f90

lnix = .FALSE.

lnix = .TRUE.

sfc_terra_snow.f90

```
PUBLIC :: snow_single_prepare
PUBLIC :: snow_single_soil_forcing
PUBLIC :: snow_single_melt
PUBLIC :: snow_single_calc_temperature
PUBLIC :: snow_single_update_new_state

PUBLIC :: snow_multi_prepare
PUBLIC :: snow_multi_handle_snowfall
PUBLIC :: snow_multi_soil_forcing
PUBLIC :: snow_multi_calc_heat_conduction
PUBLIC :: snow_multi_melt
PUBLIC :: snow_multi_update_new_state

PUBLIC :: snow_nix_prepare
PUBLIC :: snow_nix_handle_snowfall
PUBLIC :: snow_nix_energy_balance
PUBLIC :: snow_nix_mass_balance
PUBLIC :: snow_nix_update_new_state
```

NIX modules

- New snow density
- Adding snowfall
- Heat equation
- Phase changes
- Water transport
- Compaction
- Updating state

Development status for NIX in TERRA



Status:

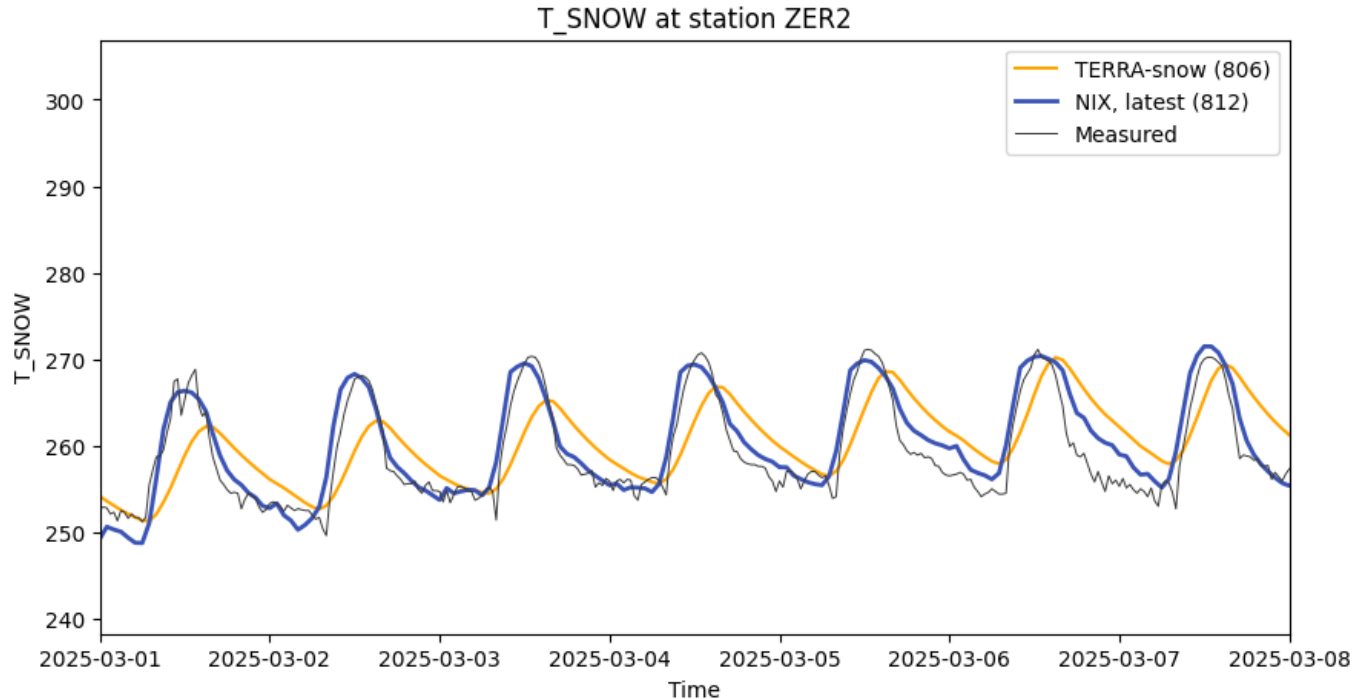
- Implementation has been finalized
- NIX branch now passed Scientific Review
- Buildbots are green
- Technical review ongoing
- Merge expected very soon now!

Features:

- Fully integrated into the heat and mass balance of TERRA
- We removed the per-tile enabling/disabling: NIX is now either active for all tiles, or none
- Support for forest tiles in similar approach as with the single layer scheme
- Support for snow analysis (IAU snow increments)
- Support for APT parameters
- First version of a glacier model



Snow surface temperature (T_{SNOW})



Single layer snow model has delayed response to the surface energy balance, due to the high heat capacity of the single layer

The multi-layer NIX model has shallow surface layers, that respond much faster, in excellent agreement with T_{SNOW} measurements.



Limitations

- Only consistent when snow cover fraction is either 0% or 100%: thus, it only works with:
`lsnowtile = .TRUE.`
- Not fully energy- and mass balance conserving, for example caused by:
 - o Using implicit boundary conditions for numerical stability
 - o Maintaining glacier ice thickness
- Several tunings have not been evaluated in-depth, such as:
 - o Albedo and snow-cover fraction parameterizations
 - o APT parameters (included, but not fully tested)
 - o Several tuning approaches in TERRA are not tested (for example: if using `idiag_snowfrac == 20`, it is recommended to switch to `idiag_snowfrac = 2` when enabling NIX).
- Not all setups supported:
 - o Requires snowtiles
 - o Does not yet support nested domains that start during runtime

A word on the merge request process

- Due to a variety of reasons, the merge request takes a long time, and has led to frustrations with all parties involved
- Scope creep:
 - o going from: a snow model for the Swiss setup that leads to improvements for MCH forecasts and can be used for some land use classes, with potential future expansion
 - o to NIX also having a glacier model, including modifications for forests, having support for APT parameters, having support for future changes in turbtran, checking inlining of functions, and vectorization on NEC, provides neutral to positive results for all global setups, all in one merge request and one review process
- It was difficult to agree on the minimum requirements for merge

I think we should all do our best to avoid this in the future, otherwise developing for ICON becomes painful and unattractive.



Next steps / Outlook

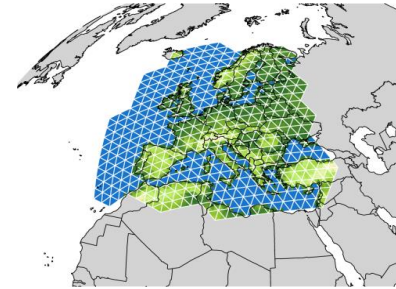


- Merging with main (should be within weeks now)
- Testing at MCH in parallel suite for winter 26/27
- Scientific publication (paper)
- Update of stand-alone version (with help of AI-coding agents)
- Dust has to settle a bit...

Personnel information:

- Nora Helbig will start on Oct. 1 as my successor
- Master student Antonia Berndt from the University of Bern for 11 months to further validate and test NIX

Extending the skin-temperature scheme to snow-covered grid points



Günther Zängl

COSMO-GM 2026, Rome, September 14, 2026

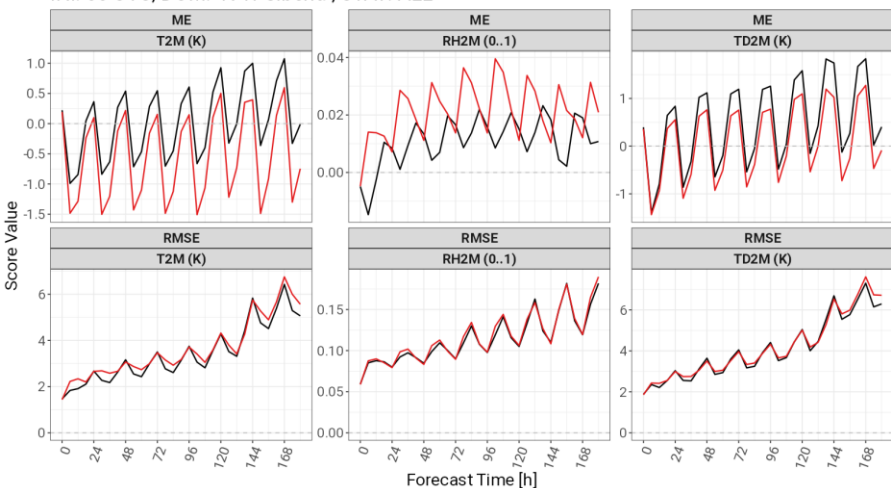
- So far, the skin-temperature scheme is restricted to snow-free grid points
- In the context of the NIX implementation, the idea came up to test extending the skin-temp to snow-covered grid points
- Indeed, significant improvements can be achieved for the diurnal temperature amplitude, particularly over deep snow layers
- Moreover, the improved diurnal temperature cycle allows changing the predictor for the adaptive snow albedo, giving daytime temperature biases a larger weight (3x) than nocturnal ones
- Namelist changes:
 - `itype_canopy = 3` (oper. 2)
 - `icpl_da_snowalb = 4` (oper. 3)



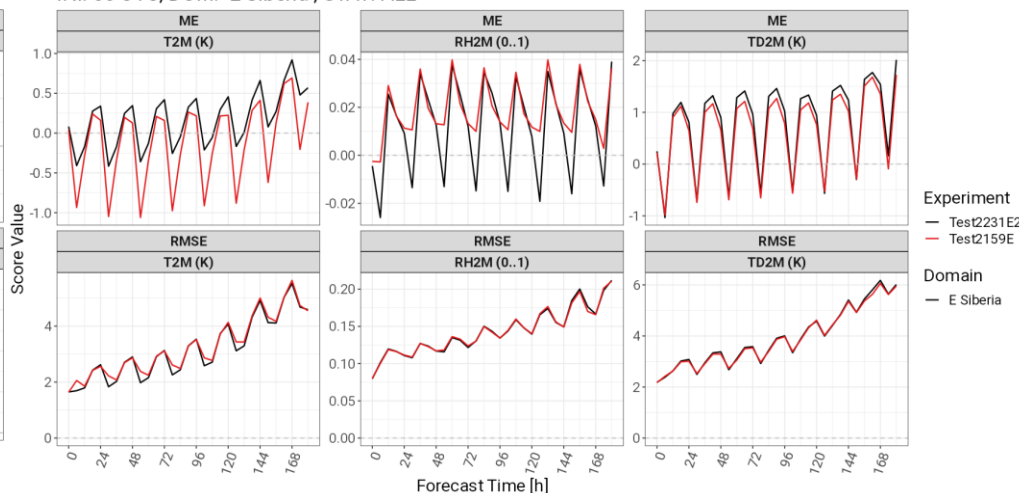
- Rather than discriminating between snow-free and snow-covered grid points, the weighted average of t_s and t_{snow} enters into the calculation of t_{sk}
- As a consequence, t_g equals t_{sk} over all land points
- The skin conductivity is parameterized based on snow depth rather than land-cover class
- Reason: the single-layer snow scheme underestimates the diurnal temperature cycle over snow primarily for deep snow layers (due to their large heat capacity)
- Moreover, minor adaptations were made to the transfer coefficient limiter and to the calculation of evaporation over snow
- Beyond that, the algorithm of the skin-temperature scheme remains unchanged
- Experiment period: January – June 2025; global ICON with full DA cycle including EPS forecasts; verification split into two-month sub-periods

➔ Strong dependence on amount of insolation (not surprising, because both the diurnal temperature amplitude and the sensitivity to surface albedo depend on solar radiation input)

2025/03/01-00UTC - 2025/04/17-00UTC
INI: 00 UTC, DOM: N-W Siberia, STAT: ALL



2025/03/01-00UTC - 2025/04/17-00UTC
INI: 00 UTC, DOM: E Siberia, STAT: ALL



Score changes of RH2M/TD2M are not always positive, but T2M is consistently improved;
changes of daytime mean bias primarily originate from the revised predictor for albedo tuning



- Extending the skin-temperature parameterization to snow-covered grid points significantly improves the diurnal temperature amplitude over thick snow layers
- Combined with an adapted predictor for the adaptive snow albedo, T2M scores are improved in most snow-covered regions
- The differences strongly depend on the amount of incoming solar radiation. They are negligible during the polar night and extend into the lower troposphere in spring and (in the Arctic) early summer



Updates on the grid- and subgrid-scale radiation-topography scheme in ICON

Christian R. Steger¹, David Leutwyler¹, Marco Arpagaus¹, and Christoph Schär²

¹ Federal Office of Meteorology and Climatology MeteoSwiss, Zürich-Flughafen, Switzerland

² Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland



Credits: www.bernerzeitung.ch / Bruno Petroni

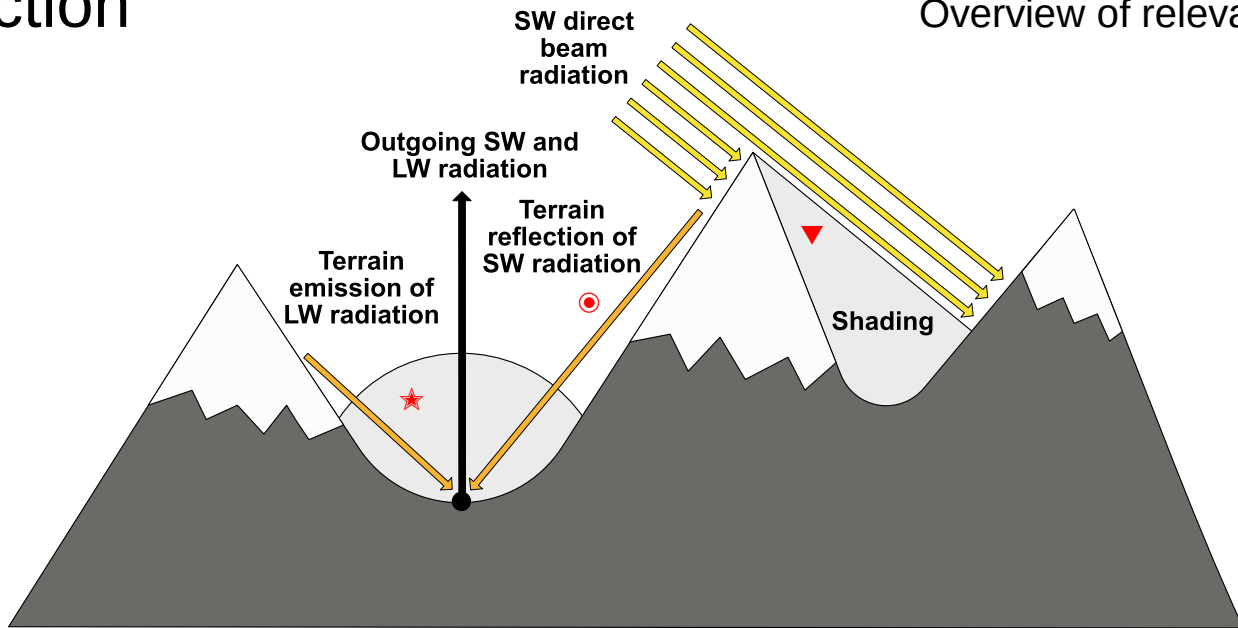


Credits: Timothy Schwitter



Introduction

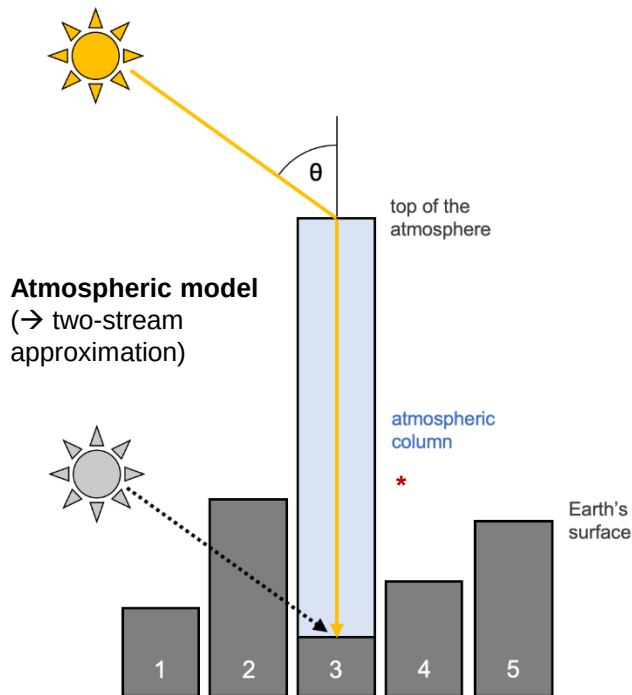
Overview of relevant processes



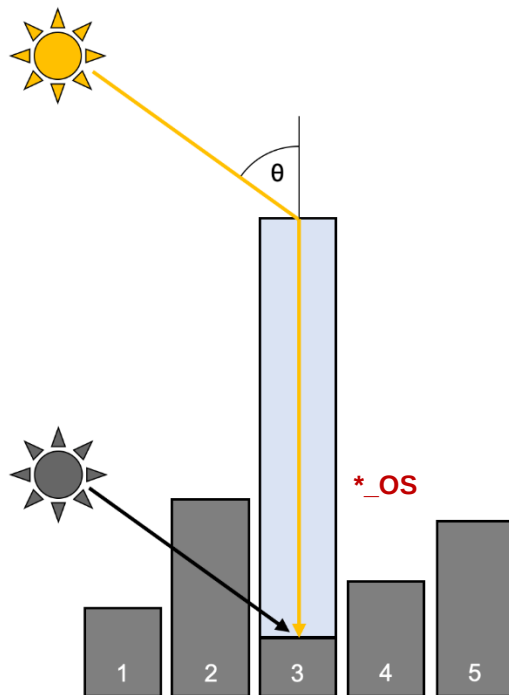
	Effect	Relevant spatial scale
▼	Incoming direct shortwave radiation (slope, topographic shading)	< than ridge-to-ridge distance (~10 km)
●	(Multiple) reflection of shortwave radiation by sloped terrain → “effective albedo” < “planar albedo”	All scales
★	Incoming longwave radiation (exchange between sloping terrain)	< than ridge-to-ridge distance (~10 km)



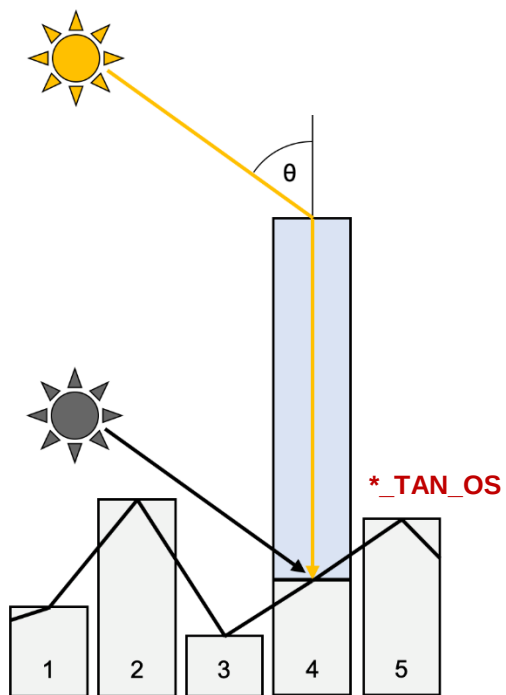
Grid-scale scheme



(a) No correction



(b) Topographic shading



(c) Topographic shading
& slope correction

Required static fields:

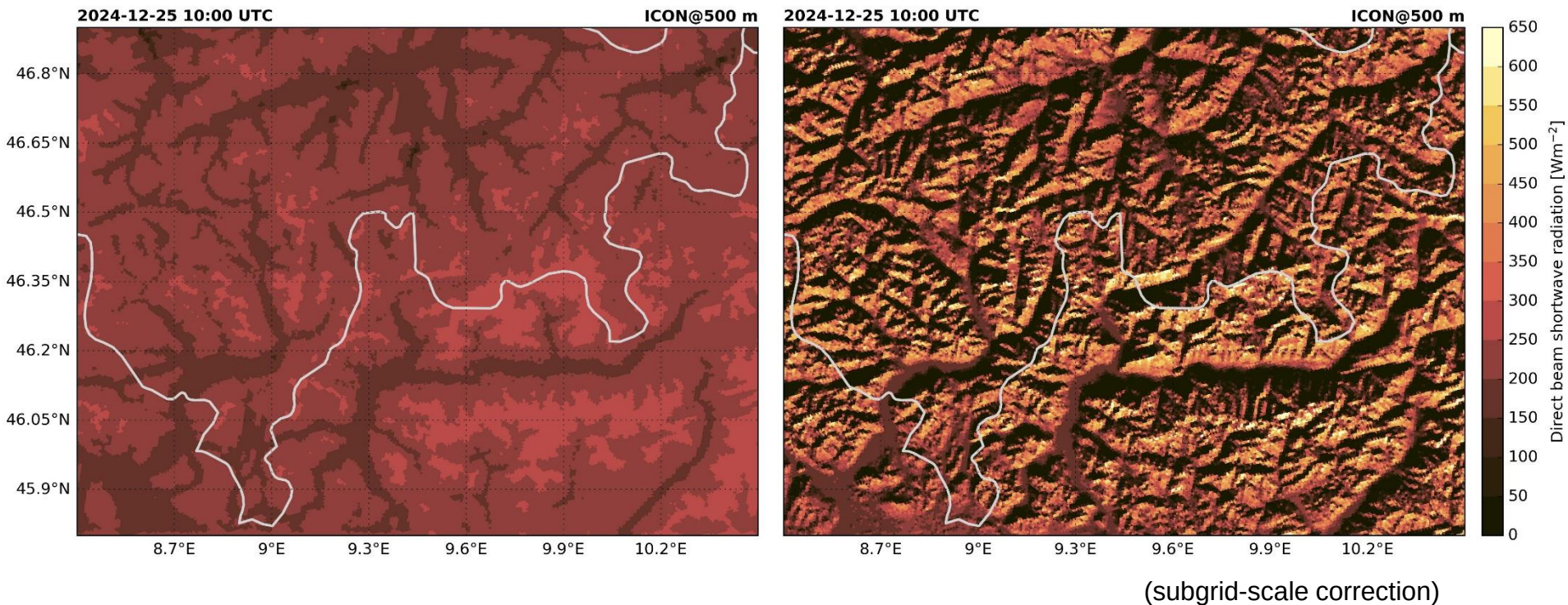
Terrain horizon

Terrain horizon, slope & aspect



Subgrid-scale parameterisation

Example of direct SW radiation



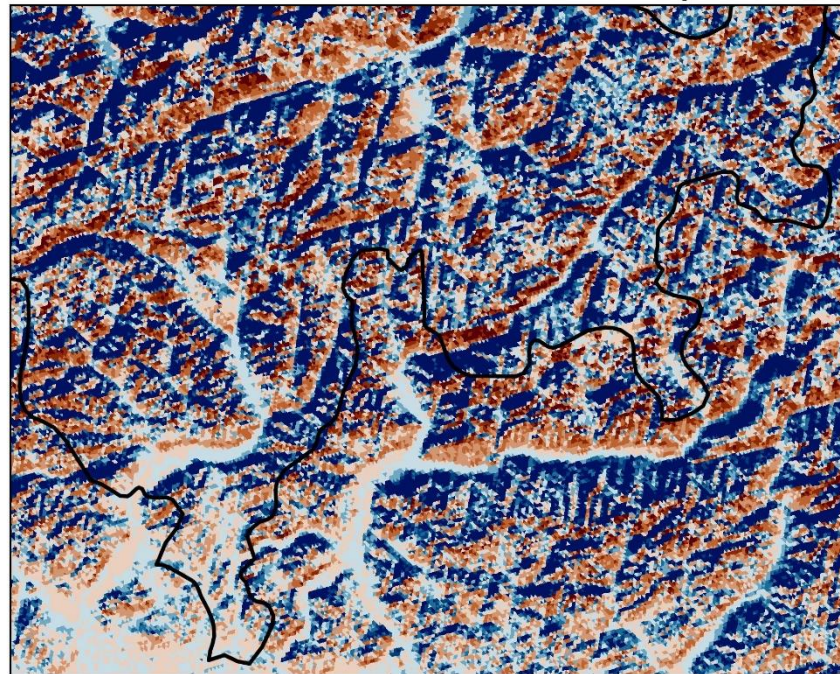


Subgrid-scale parameterisation

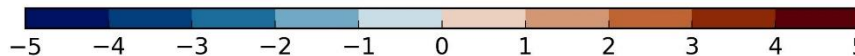
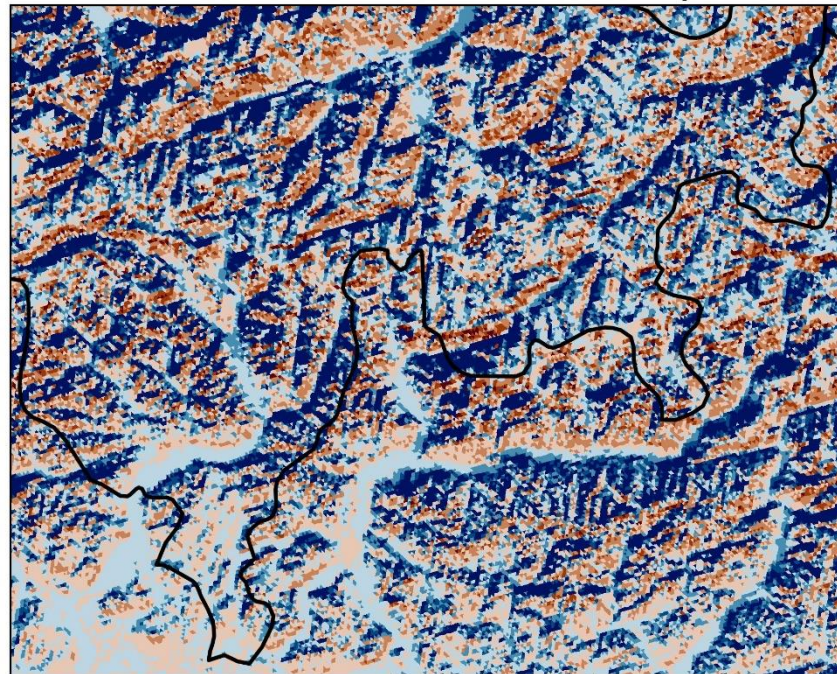
Effect on (near-)surface temperature

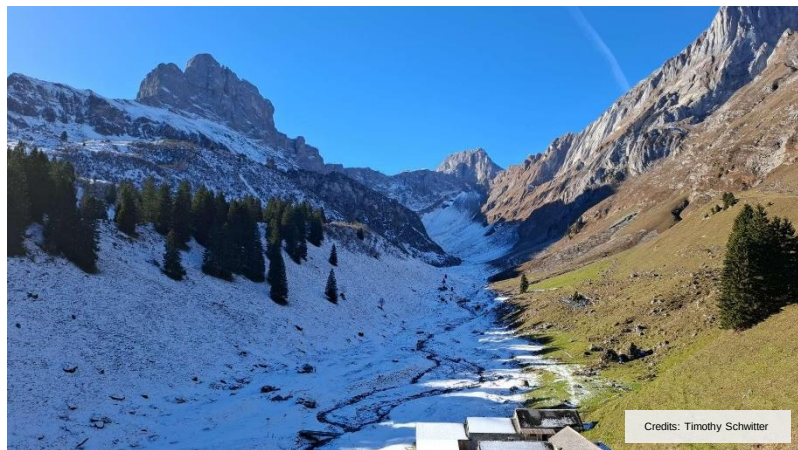
2024-11-03 10:00 UTC

Ground temperature [K]

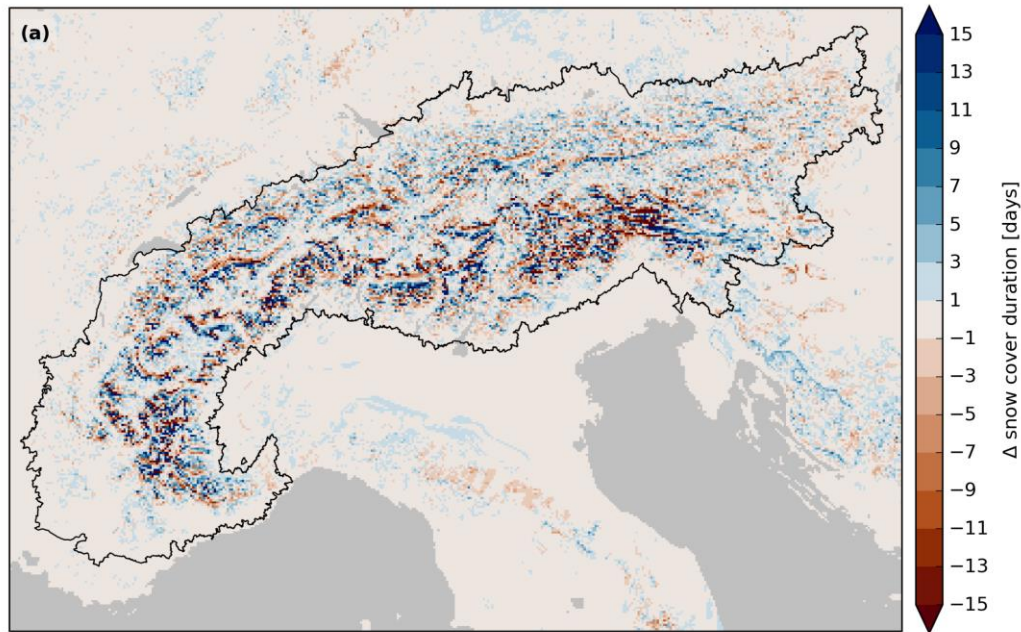


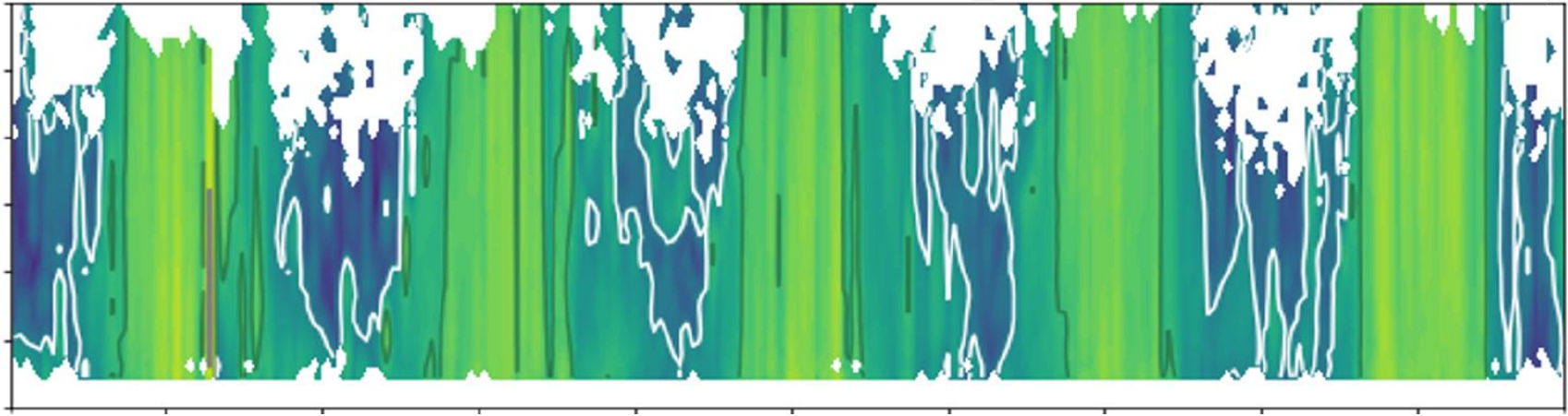
2m temperature [K]





COSMO@2km; 2018.09.01 → 2019.08.31, Radtopo minus CTRL

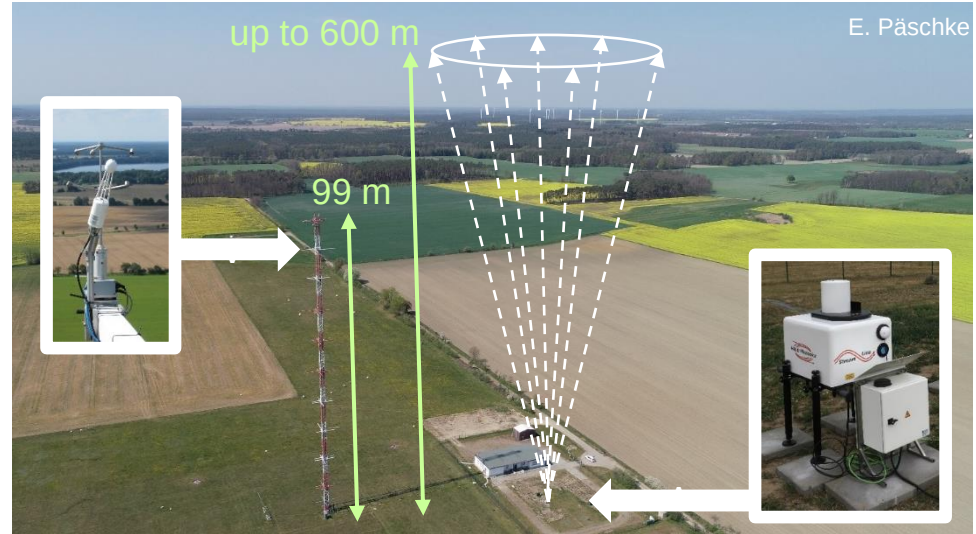




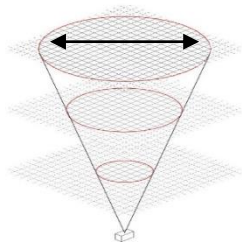
Evaluation of turbulence by Doppler lidar observations

Maike Ahlgrimm (DWD, HErZ), Eileen Päsche (DWD Lindenberg)

- Smalikho & Banakh 2017, Päsche & Detring 2023 provide a retrieval method to **simultaneously measure**:
 - winds
 - turbulent kinetic energy (TKE)
 - eddy dissipation rate (EDR)
 - turbulent length scale (L_v)
 - turbulent momentum transport
- The Doppler lidar scan configuration involves:
 - 30min continuous scans for each retrieval
 - 35.3° elevation angle
 - only the lowest ~600m of the ABL observed
 - spatial area covered by scan approximately 1700m at 600m, 280m at 100m elevation
 - TKE measured represents a **joint temporal-spatial variability** over a 30min period and a height-dependent scan circle area

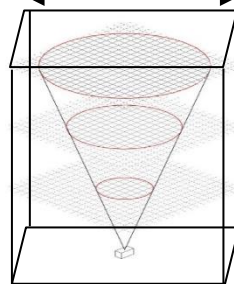


ca. 1700m



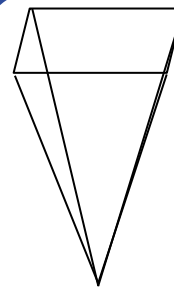
DL scan cone

2.1km



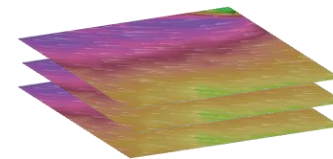
Coarse mesh size

- temporal wind variance over 30min period only
- online diagnostic every model time step



+

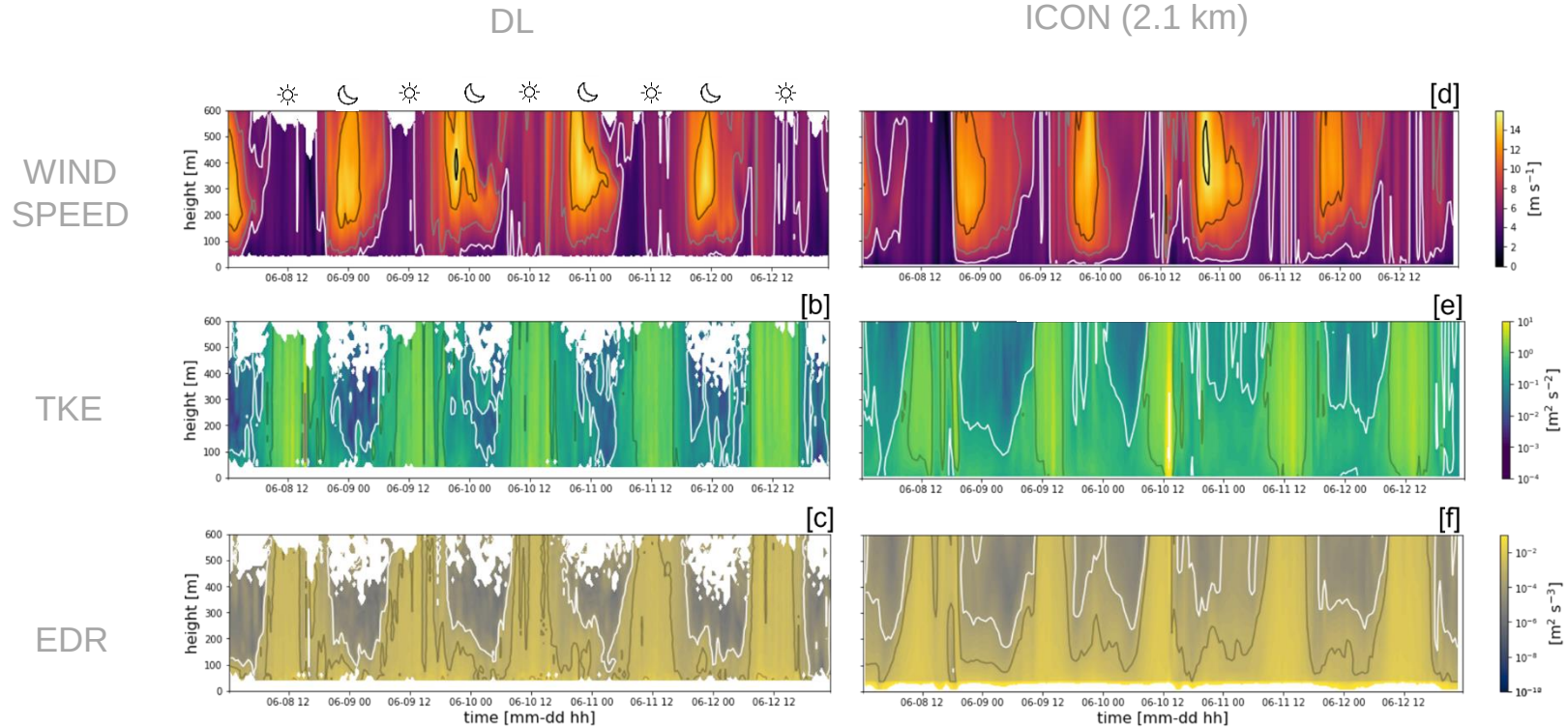
5min winds



Fine mesh size

- interpolation regular lat-lon mesh
- horizontal averaging scale varies with height
- frequent wind output (5min, 1min)

- parameterized TKE from turbulence scheme represents only **subgrid-scale** (SGS) part
- **temporal fluctuations** of **grid-scale** (GS) wind, and
- **horizontal fluctuations** of GS winds within scan cone area contribute to **GS TKE**



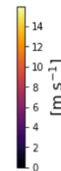
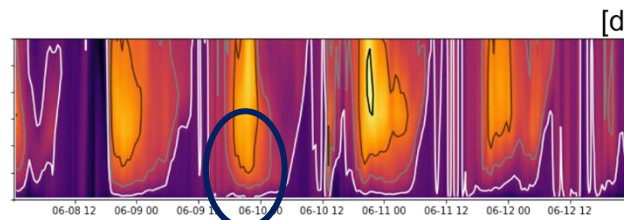
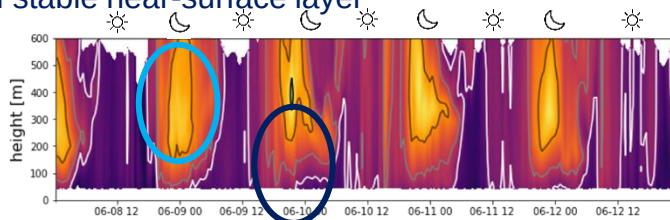


- LLJs at night
- signatures of cold pools
- discrepancies in stable near-surface layer

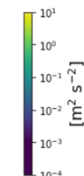
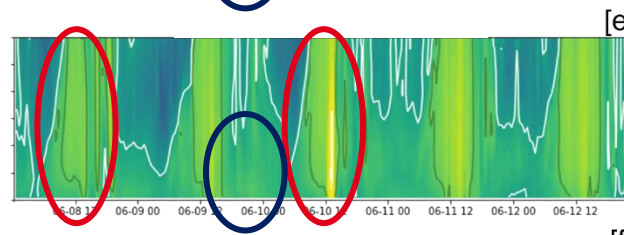
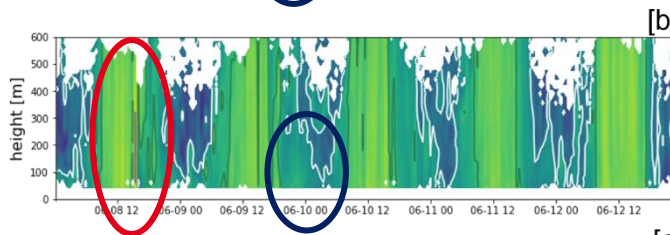
DL

ICON (2.1 km)

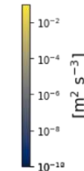
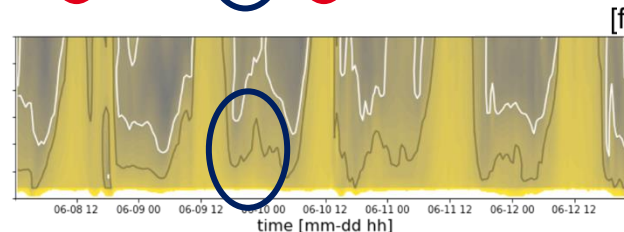
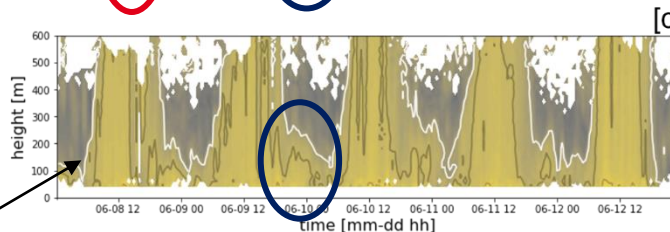
WIND
SPEED



TKE



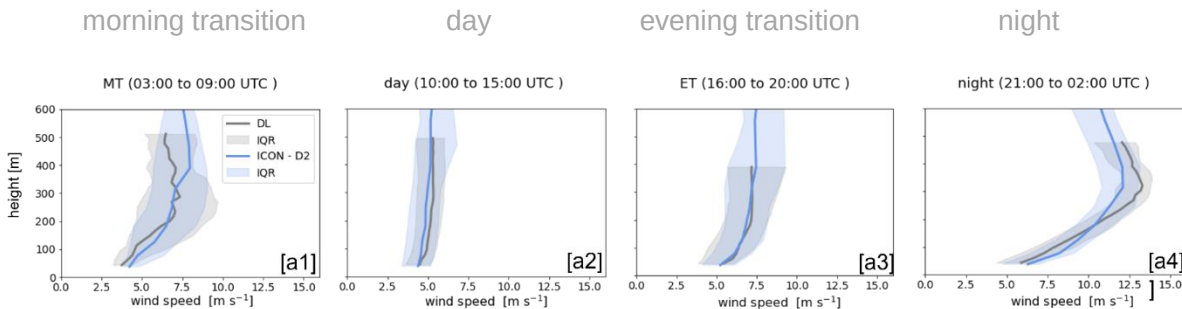
EDR



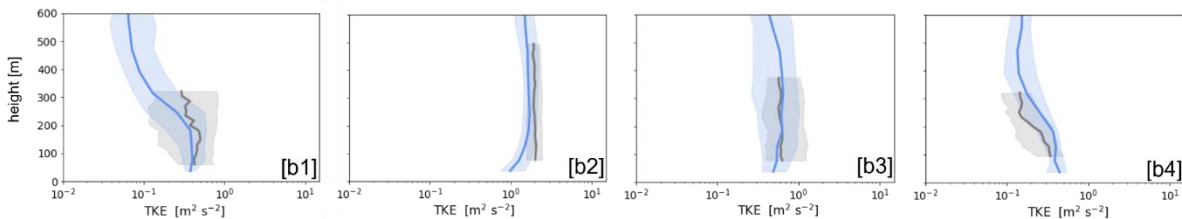
*Mixed layer
height $1e-4 \text{ m}^2 \text{ s}^{-2}$



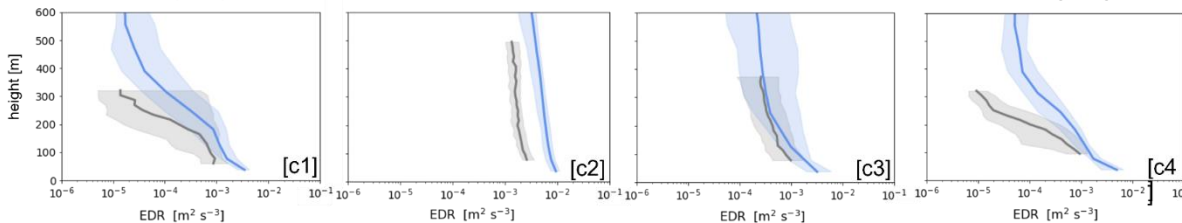
WIND



TKE



EDR



→ daytime quite good

→ LLJ max wind speed underestimated

- Doppler lidar retrieval provides **good quality, self-consistent observations** of winds, TKE, EDR and turbulent length scale in the lower ABL
- **Valuable tool** to gain insights into specific aspects of the turbulence scheme
- ICON's „Turbdiff“ scheme **performs adequately down to 78m mesh size** in terms of reproducing winds, but shows **systematic errors** representing **low-level jets** under stable conditions
- Additional parameters: turbulent length scale, momentum transport
- Interesting **follow-on applications** for wind energy, **ABL height diagnostics** based on EDR
 - **Päschke, E. and Ahlgrim, M.:** Turbulence Intensity from ICON: **A study of the potential for Wind Energy Applications**, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-9666, <https://doi.org/10.5194/egusphere-egu26-9666>, 2026. *Mon, 04 May, 16:15–18:00 (CEST) Hall X4*
 - **Baumgarten, K., Päschke, E., and Beyrich, F.:** Evaluating the **atmospheric boundary layer height from ceilometer and Doppler lidar**: Divergent retrievals across methods and the question of what they truly represent, EGU General Assembly 2026, Vienna, Austria, 3–8 May 2026, EGU26-6622, <https://doi.org/10.5194/egusphere-egu26-6622>, 2026. *Mon, 04 May, 16:15–18:00 (CEST) Hall X4 | X4.45*

- ➔ Paper is now published in GMD: Ahlgrimm and Päsche, 2026, <https://doi.org/10.5194/gmd-19-8385-2026>
- ➔ Finalize new turbulence diagnostics in model -> repeat systematic analysis of behaviour across resolutions
- ➔ Compare Turbdiff, TKE-SV, 2TE schemes
- ➔ Extend use of DL retrieval record (covers 2 years at Lindenberg), use observations from VITAL2 campaign (6 DL in Köln/Bonn/Aachen area, different retrieval algorithm)
- ➔ IAFE position at Lindenberg to pursue investigation into best use of new DL network at DWD (primary function to measure wind profiles in BL for assimilation)



Overview of Coupled ICON-A/ICON-O-LAM experience at CMCC

M. Raffa¹, A. Campanale¹, A. Campanale¹, E. Tedesco¹, P. Mercogliano¹, J. P. Schulz^{2,1}

(1) *Euro-Mediterranean Center on Climate Change (CMCC), REMHI Division, Caserta, Italy*

(2) *German Meteorological Service (DWD), Research and Development, Offenbach a. M., Germany*

www.cmcc.it

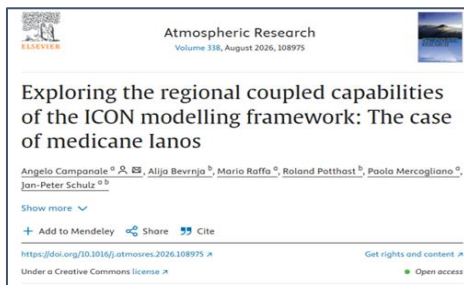


The regional coupled ocean–atmosphere of ICON at CP scale: Central Mediterranean domain



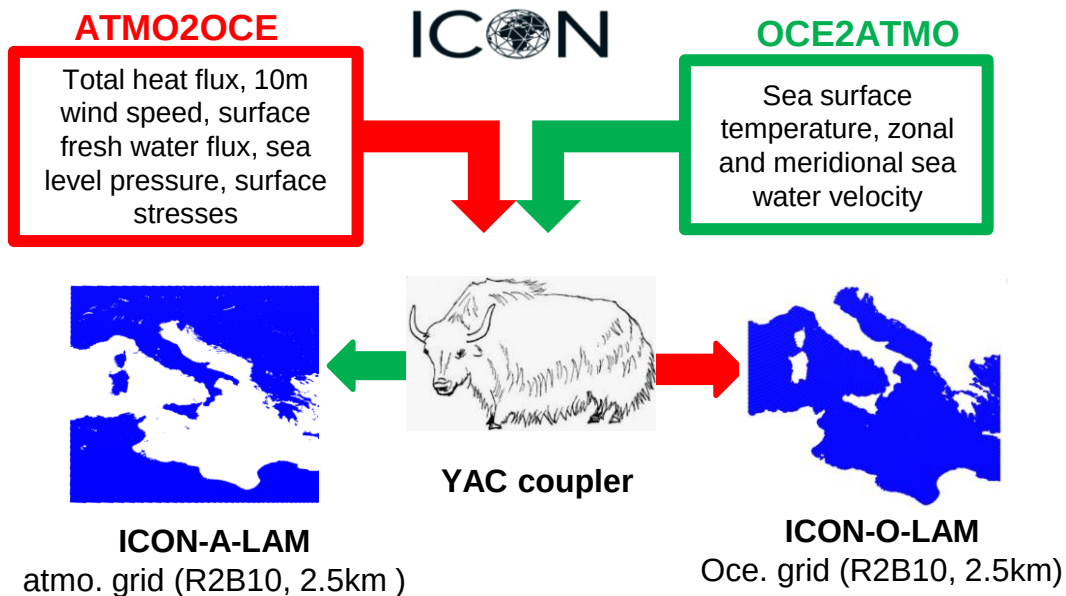
CMCC, in collaboration with DWD and in the context of the GLORI4DE project, led the development of an **ICON-based coupled ocean-atmosphere** system over the Mediterranean region:

- Design of the regional configuration of the ICON-LAM component, integrating the **ICON-Atmosphere-LAM** and **ICON-Ocean-LAM** (recently developed)
- Assessment of the coupled system for forecasting **extreme events** with strong ocean–atmosphere feedbacks (e.g., medicanes)
- Simulations over different **Medicanes** systems (Ianos, Daniel and Qendresa)



Online coupling **ICON-A-LAM** and **ICON-O-LAM** through **YAC**:

- Atmosphere: ICON-A-LAM, setup ICON-D2 (Chen et al., 2024, Campanale et al., 2025)
- Ocean: ICON-O-LAM, setup with 50 levels from 0.5 to 54965 m (Korn et al., 2022, Jungclaus et al., 2022)
- Coupler: YAC (Hanke et al., 2016)
- IC and BC from IFS analysis for atmosphere component (6hr)
- IC and BC from CMEMS reanalysis for ocean component (24 hr)



The Workshop on regional ICON Coupled atm-ocean *Italian initiative*



Hosted by the REMHI (Regional Models and GeoHydrological Impact) Division of CMCC, Caserta.

Objective: assess the state of the art of ICON-based coupled regional modelling in Italy, comparing the coupled system in the operational chain of participants and outline a coordinated strategy under the COSMO Consortium.

CMCC

REMHI Division
Institute for Climate Resilience

Caserta



CETEMPS

Centre of Excellence,
University of L'Aquila

L'Aquila



Scope

Assess the state of the art of ICON-based coupled regional modelling in Italy and outline a coordinated strategy under the COSMO Consortium

Key findings

- ICON-O-LAM is a promising and architecturally efficient route to fully coupled regional simulations — integrated atmosphere–ocean namelist, consistent with the global ICON framework
- Campanale et al. (2026) on medicane lanos: proof of concept and reference benchmark; CMCC–DWD partnership ensures continuity with the official ICON development line
- Building blocks already available (grid preparation, downscaling, initialisation, coupling)
- Priority gaps: missing consolidated documentation and benchmark configurations for ICON-O-LAM; incomplete characterisation under high-impact regimes, including sensitivity to ocean boundary forcing

Arpae

Regional Agency for Prevention,
Environment and Energy of Emilia-
Romagna

Bologna



CNMCA

Italian Air Force
Meteorological Service

Pratica di Mare



Anchored on Campanale et al. (2026, Atmospheric Research) and on the CMCC–DWD collaboration on ICON coupled development at regional scale.