Project: **1096**
Project title: **Turbulence resolving simulation of atmospheric boundary layer processes**
Principal investigator: **Juerg Schmidli**
Report period: **2025-11-01 to 2026-10-31**

The goal of this project is to improve the representation of the ABL in weather and climate models with a focus on: 1) scale-adaptivity, and 2) complex-terrain boundary layers. For this purpose experiments on Levante were performed according to the proposal of the project. Here we present a selection of substantial results following from the simulations. Further results can be found in our new publications listed on the DKRZ project website.

a) Development of a scale-adaptive unified parametrization for ABL turbulence and boundary-layer clouds

a.1) Representation of transitional atmospheric boundary layers

We analysed shallow-cloud statistics from ICON-LES and developed a cloud-base mass-flux closure for stochastic extension of the two turbulence energies scheme (2TE; (Bašták Durán et al., 2022)). The corresponding manuscript is accepted for publication in *Journal of Advances in Modeling Earth Systems* (Singh et al., 2026). The resulting scale-aware scheme (2TE-S) has been implemented and assessed in idealized simulations. In parallel, we evaluated cloud statistics from ICON-NWP simulations over the Alps and adjoining lowlands against SEVIRI observations. Preliminary results show that the 2TE scheme substantially improves the simulated cloud reflectance and brightness-temperature distributions compared with the TKE scheme. The overestimated cloud fraction (C_n) is reduced from 61% (TKE) to 52% (2TE), approaching the observed 47% (see Figure 1). A manuscript presenting these findings is in preparation.

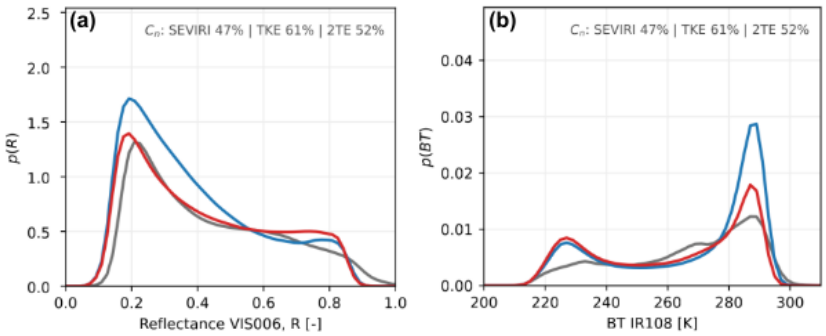


Figure 1: (a) PDF of the 0.6 μm reflectance, $p(R)$, and (b) PDF of the 10.8 μm brightness temperature, $p(\mathrm{BT})$, over the Alps and adjoining lowlands for SEVIRI observations (grey), ICON with the TKE scheme (blue) and ICON with the 2TE scheme (red). The number fraction of cloudy pixels, C_n, is given in each panel.

a.2) Impact of small-scale dynamics on UTLS transport and mixing

The study of overshooting deep convection over the Alps has been published (Alladi et al., 2026). The results demonstrate that turbulence parameterizations primarily affect the timing and spatial extent of convection, whereas microphysics has a greater impact on hydrometeor distributions and cross-tropopause transport.

Building on this work, we investigated convective moisture transport into the upper troposphere and lower stratosphere (UTLS) over the Tibetan Plateau during the Asian summer monsoon. We compared kilometre-scale ICON simulations with ERA5 reanalysis and satellite observations. Under deep convective conditions at the UTLS, ICON simulated higher water-vapour concentrations and agreed more closely with Microwave Limb Sounder observations than ERA5, suggesting improved representation of convection-associated moisture transport into the UTLS. A manuscript reporting our findings is currently under preparation.

b) Analysis of complex-terrain ABLs and the development of suitable subgrid-scale (SGS) models

b.1) Cold air pool modelling and pollution in complex terrain

We developed a framework to identify severe pollution events in Bogotá, Colombia, dominated by local emissions while minimizing the influence of regional pollution transport. Statistical filtering of PM_{10} observations from the Bogotá air-quality network (2018–2022), combined with trajectory analysis, identified three representative events, which were simulated using a high-resolution nested ICON configuration and evaluated against surface observations.

The simulations reproduced key meteorological conditions and revealed recurrent nighttime and early-morning stagnation and recirculation under stable boundary-layer conditions. Weak ventilation and persistent stagnation in the southern and southwestern Bogotá coincided with observed PM_{10} hotspots and strong local emissions, notably resuspended dust. This work was conducted as part of a Master's thesis at Goethe University Frankfurt.

b.2) The impact of thermally driven wind systems on exchange over complex terrain

We assessed the impact of small-scale orography and thermally driven wind systems on the dry-season deep ABL over the Tibetan Plateau using high-resolution LES with CM1. Transport and exchange were investigated using surface-based and upper-level passive tracers in three configurations: a flat plateau, realistic orography, and realistic orography with a constant upper-level background wind. The research showed that small-scale orography sustains and organizes turbulence over the Tibetan Plateau, thereby enhancing ABL mixing and contributing to the exceptionally deep ABLs forming under weak free-tropospheric stability during springtime. The manuscript reporting our findings has been published in *EGUsphere* (Basic et al., 2026).

b.3) Modelling tracer transport and mixing in the ABL over complex terrain

The study advanced to high-resolution semi-idealized CM1-LES with realistic topography and time- and spatially varying tracer fluxes representative of CO_2 to investigate passive-tracer accumulation in nocturnal cold-air pools and its depletion during the morning transition. The simulations reveal substantial spatial and temporal variability in stable boundary-layer height and tracer concentrations, depending on valley geometry, and orographic waves generated by the background wind. Compared with tall-tower observations, simulations show a shallower stable boundary layer and earlier, faster depletion, likely reflecting domain and tracer-footprint limitations, idealized boundary conditions, and uncertainties in land–atmosphere coupling and model parameters. The manuscript is currently in preparation for submission to *Boundary-Layer Meteorology* in November 2026 (Basic and Schmidli, 202x).

We also investigated the vertical mixing of CO_2 in hindcast ICON-NWP simulations for selected summer and winter months, comparing the operational turbulence scheme with our recently developed 2TE scheme. Both schemes reproduced the general diurnal CO_2 cycle but systematically underestimated peak concentrations in the morning, whereas daytime biases remained small and differences between the two schemes were negligible. We found that local flows shaped by complex orography strongly control the CO_2 distribution in convergence zones and shallow valleys, highlighting the uncertainties in local tracer transport as a limiting factor for robust emission verification in complex terrain. A manuscript reporting our findings is currently under preparation.

b.4) Interaction of Foehn flows with the ABL

We published a comparison study of COSMO and ICON for south foehn in the Alpine Rhine Valley in *QJRMS*, demonstrating better near-surface performance of ICON (Tian et al., 2026). Building on these findings, we investigated foehn descent in one case study using LAGRANTO forward and backward trajectories from nested ICON-LES with grid spacings from 520 m to 130 m. Forward trajectories confirm that foehn descent is concentrated in a few hotspots whose locations vary with model resolution. Backward trajectories from identical downstream seeding locations also reveal resolution-dependent differences in pathways, distance travelled and propagation speed.

References

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