3D Radiative Transfer for ICON-LEM

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HD(CP)^2 High definition clouds and precipitation for advancing climate prediction

Convective Organization Depends on Radiative Transfer Solver

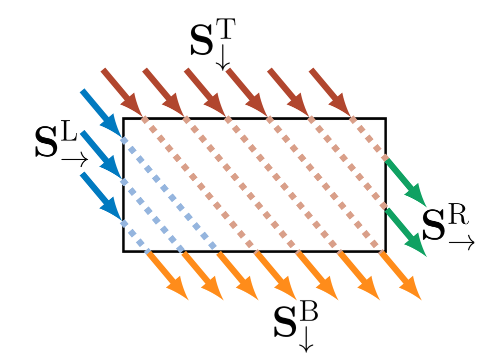
Our results in [1] suggest that solar radiative heating has the potential to organize clouds depending on the sun's incidence angle. Over land, these 3D effects may significantly alter the boundary layer dynamics and cloud development on a timescale of half an hour. Studying these in a more realistic setup is our motivation to implement 3D radiative transfer into ICON-LEM.

1D Radiative Transfer

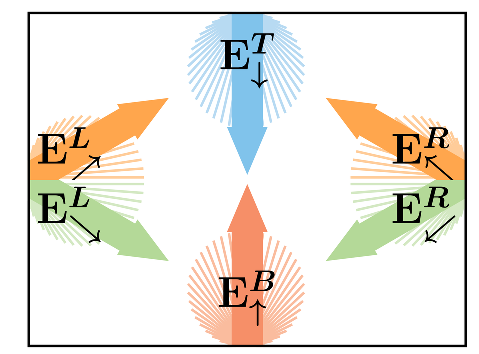
3D Radiative Transfer

Virtual photographs of LES simulations, as seen from a cruising altitude of 15 km. The cloud simulations either use 3D or 1D Radiative-Transfer calculations and show differences with respect to cloud size distribution and the organization in cloud streets. Both visualizations are performed with MYSTIC (physically correct MonteCarlo renderer in libRadtran [6, 7]).

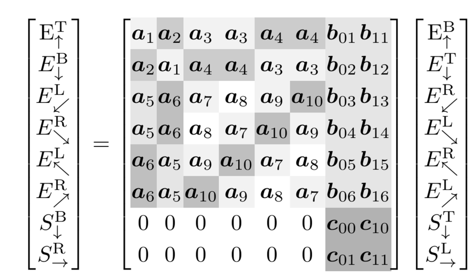
Concept for a new Solver



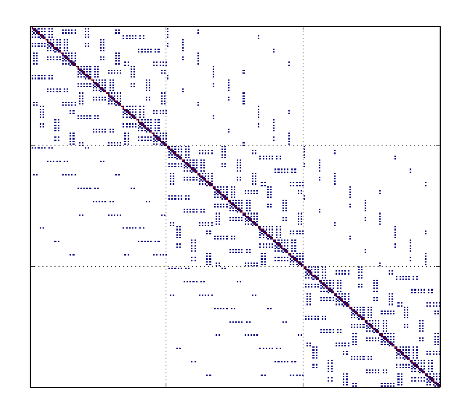
Discretize radiation streams angularly and spatially → at least 5 streams (one for each face) for direct radiation (fixed angle)



Diffuse angular discretization assumes Lambertian surfaces. Two streams (up- and downward), as in 1D solver.
Additional streams sidewards allow for horizontal energy transfer



Use MonteCarlo to compute transport coefficients for single boxes and couple to neighbors
→ huge, but sparse matrix

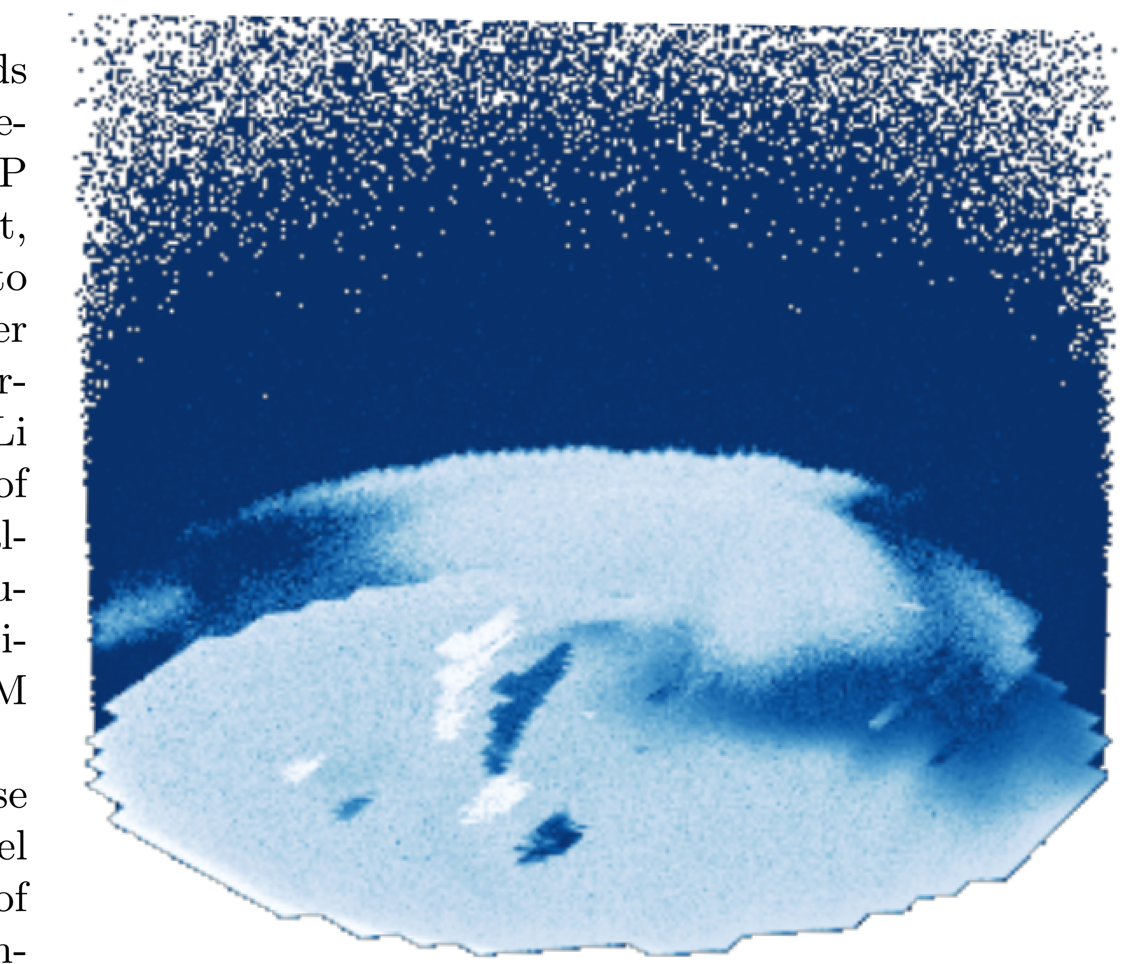


Solve linear equation system with parallel iterative methods (PETSc):
ASM + SOR or GMRES + Algebraic Multigrid (GAMG)

RayLi

The Ray based Light Simulator (RAYLI) is a 3D MonteCarlo ray-tracing library which can be used on the native ICON-Mesh. The concept of a MonteCarlo solver for radiative transfer is the idea that we trace photon paths through the atmosphere and statistically solve the integral in the radiative transfer equation. The beauty of MonteCarlo raytracing is the flexibility and accuracy. We can consider complex atmospheric scenes without the need for any simplifications.

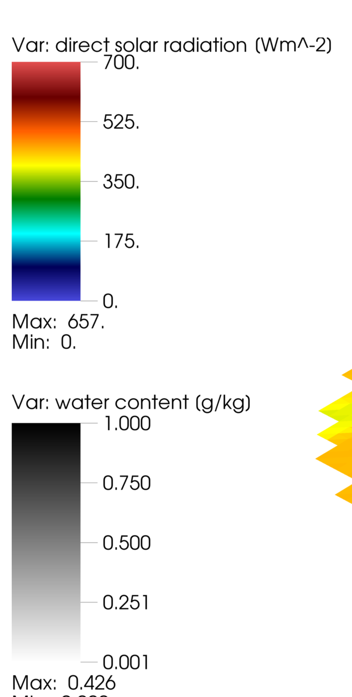
However, MonteCarlo methods are computationally too demanding to be run in NWP or LES models directly. Yet, they are superb candidates to benchmark radiative transfer parameterizations. One particular feature of the RayLi library is the abstraction of the underlying mesh which allows a straightforward coupling with the TenStream library and the ICON-LEM grid.
In the following, we will use RayLi as a benchmark model to assess the performance of the TenStream solver on unstructured meshes.

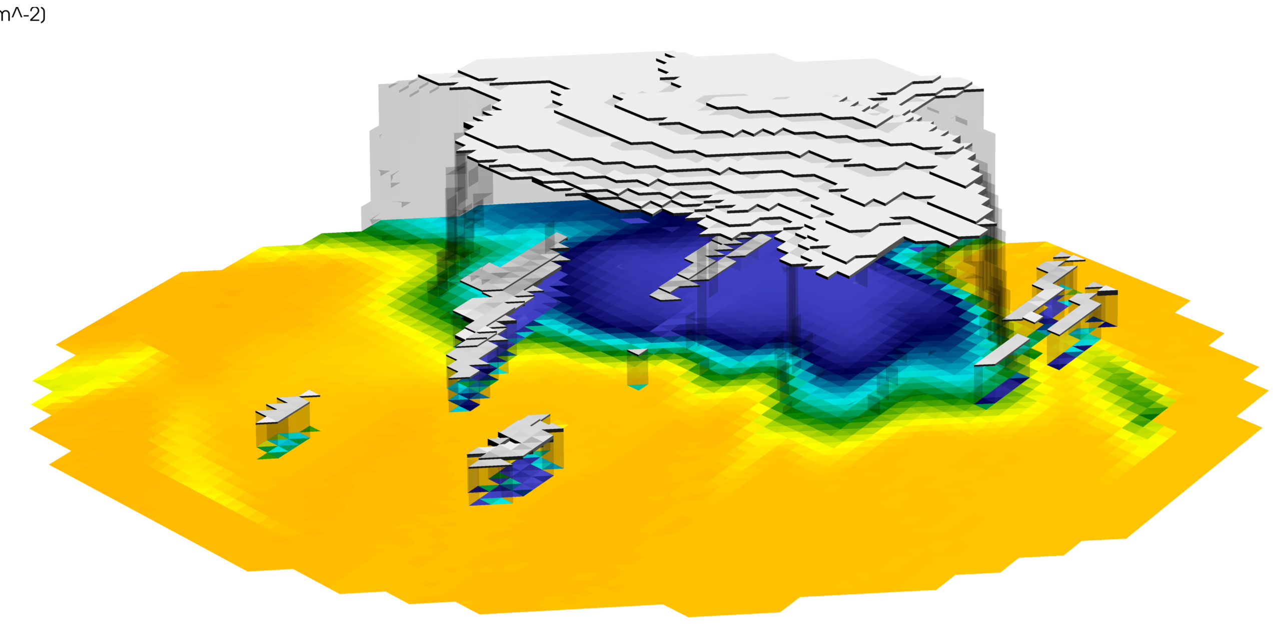


- virtual photograph of an ICON-LEM scene, rendered with RayLi within the TenStream

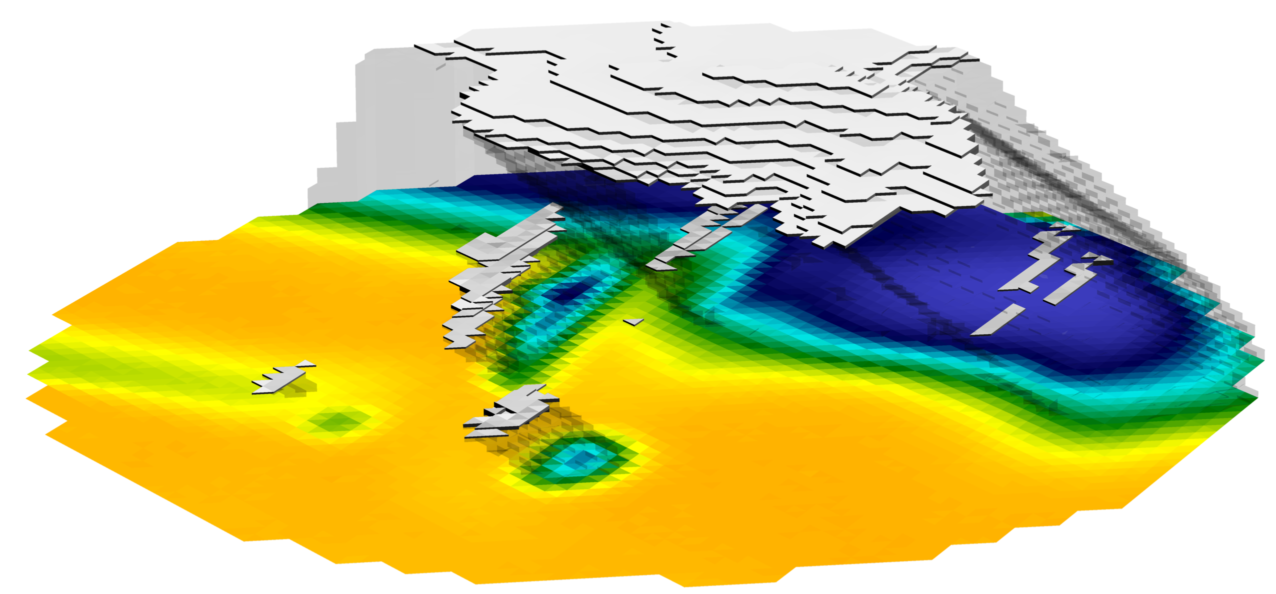
3D Effects of Direct Solar Radiation in ICON-LEM and Validation against "RayLi"

This panel depicts results for direct solar radiation for several radiative transfer solvers in an ICON-LEM simulation with a horizontal resolution (edge length) of 1.2 km (solar zenith angle is 61°, surface albedo is constant).

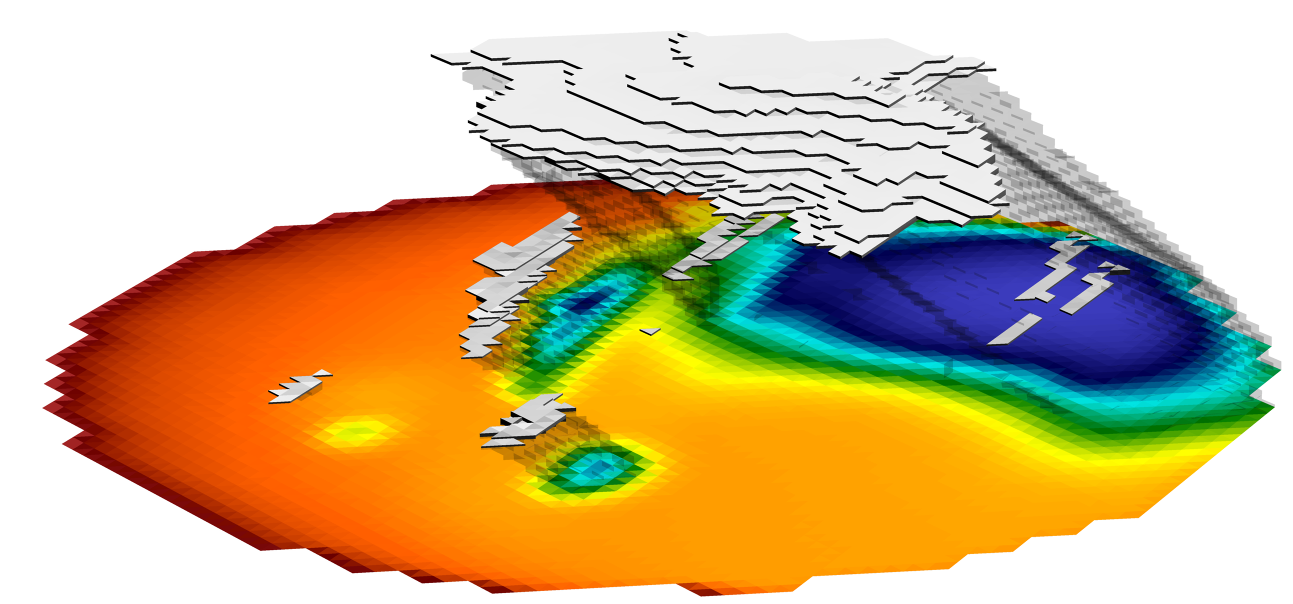




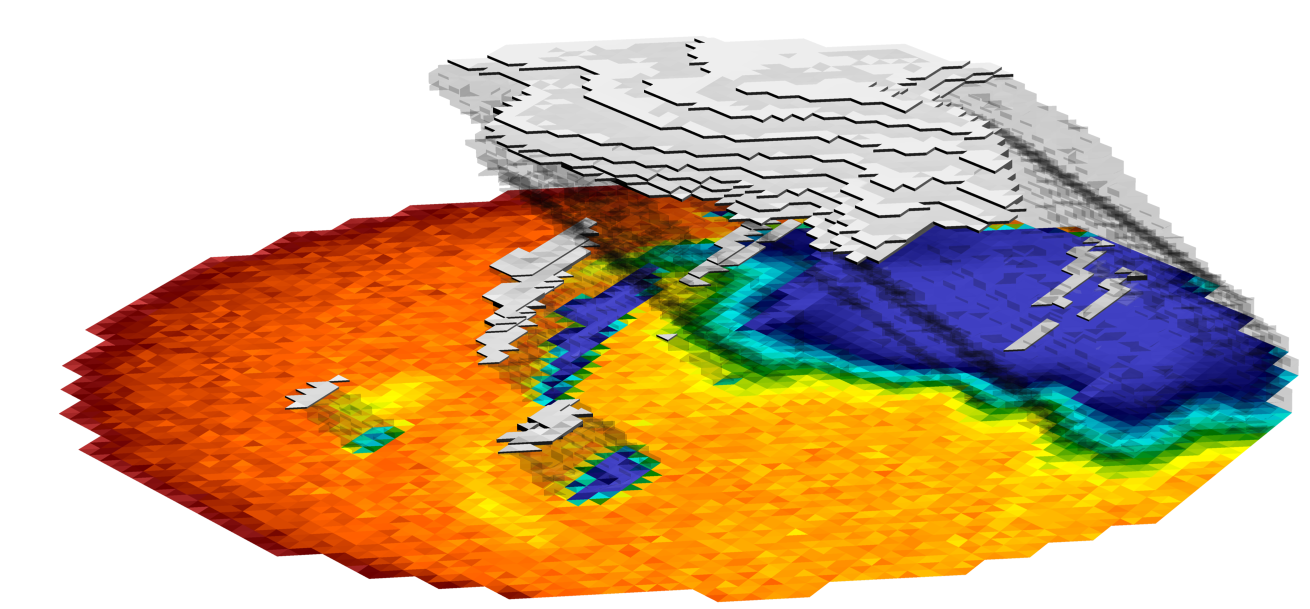
- 1D δ-Eddington solution
- lacks horizontal transport of radiation and hence erroneously places the shadow always directly beneath clouds



- TenStream solver on the ICON mesh
- produces realistic radiative fluxes and heating rates



- TenStream solver on the ICON mesh, here with vacuum boundary conditions outside of the domain
- allows a comparison to the MonteCarlo benchmark results with RayLi



- RayLi MonteCarlo results
- no numerical diffusion as seen with the TenStream solver (e.g. visible by smoothed surface shadows)

References

[1] F. Jakub and B. Mayer. "The Role of 1D and 3D Radiative Heating on the Organization of Shallow Cumulus Convection and the Formation of Cloud Streets" ACP (2017).
[2] C. Klinger et. al. "Effects of 3D Thermal Radiation on Cloud Development" ACP (2017).
[3] F. Jakub, "On the Impact of Three Dimensional Radiative Transfer on Cloud Evolution" LMU (2016).
[4] F. Jakub and B. Mayer. "A Three-Dimensional Parallel Radiative Transfer Model for Atmospheric Heating Rates for use in Cloud Resolving Models–the TenStream solver." JQSRT (2015).
[5] F. Jakub and B. Mayer. "3D Radiative Transfer in Large-Eddy Simulations – Experiences coupling the TenStream solver to the UCLA–LES" GMD (2016).
[6] C. Emde et. al. "The libRadtran Software Package for Radiative Transfer Calculations" GMD (2015).
[7] B. Mayer. "Radiative transfer in the cloudy atmosphere." EPJ (2009).