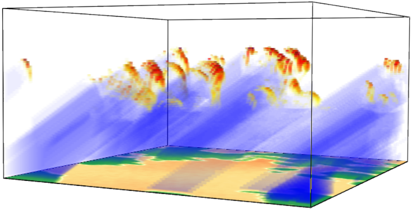
Three Dimensional Radiative Transfer Effects in Numerical Weather Prediction and Large Eddy Simulations – Methods and Impact on Cloud Evolution and Precipitation

F. Jakub[1], J. Schäfer[2], P. Gregor[2], H. Böttcher[2], F. Negwer[2], R. Maier[2], M. Veerman[2], C. Klinger[2], B. Mayer[2]

[1] DWD — German Weather Service
[2] LMU — Meteorological Institute Munich



Nov 18, 2024

History of Radiative Transfer

Radiative Transfer theory well established

- radiative transfer equation (1960 Chandrasekhar)

$$\frac{\mathrm{d}L}{k_{\mathrm{ext}} \cdot \mathrm{d}s} = -L + \frac{\omega_0}{4\pi} \int_{4\pi} p(\Omega', \Omega)\, L(\Omega')\, \mathrm{d}\Omega' + (1 - \omega_0) B_{\mathrm{Planck}}(T)$$

Radiative Transfer theory well established

- radiative transfer equation (1960 Chandrasekhar)

$$\frac{\mathrm{d}L}{k_{\mathrm{ext}} \cdot \mathrm{d}s} = -L + \frac{\omega_0}{4\pi} \int_{4\pi} p(\Omega', \Omega)\, L(\Omega')\, \mathrm{d}\Omega' + (1 - \omega_0) B_{\mathrm{Planck}}(T)$$

- surprisingly well working 1D approximations
- sophisticated 3D models since the 90's (e.g. MonteCarlo)

Radiative Transfer theory well established

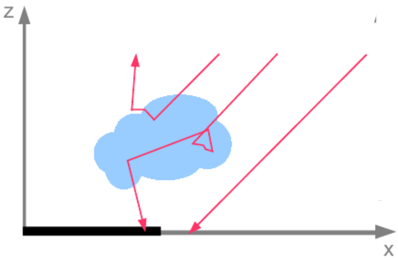
- radiative transfer equation (1960 Chandrasekhar)

$$\frac{\mathrm{d}L}{k_{\mathrm{ext}} \cdot \mathrm{d}s} = -L + \frac{\omega_0}{4\pi} \int_{4\pi} p(\Omega', \Omega)\, L(\Omega')\, \mathrm{d}\Omega' + (1-\omega_0) B_{\mathrm{Planck}}(T)$$

- surprisingly well working 1D approximations
- sophisticated 3D models since the 90's (e.g. MonteCarlo)
- ... but orders of magnitude too slow to run in atmospheric models

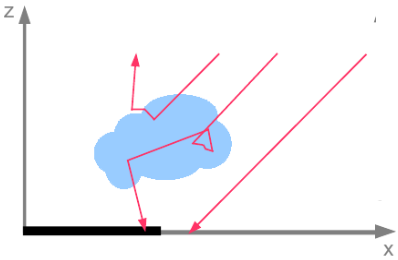
Approximations for Radiative Transfer

Radiative transfer describes photon interactions with atmosphere.
MonteCarlo modelling of scattering and absorption:



Approximations for Radiative Transfer

Radiative transfer describes photon interactions with atmosphere.
MonteCarlo modelling of scattering and absorption:

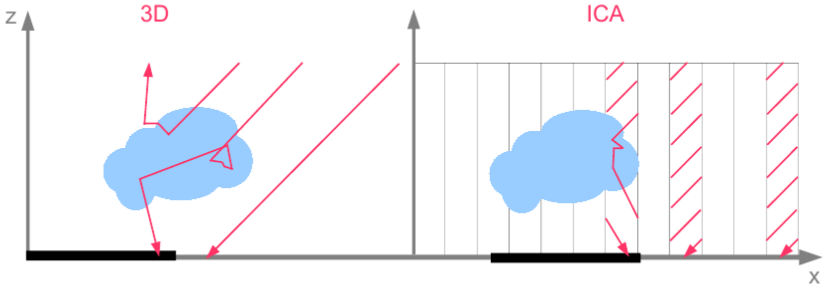


simplify to solve:

- Plane Parallel approx.
- Independent Column approx.

Approximations for Radiative Transfer

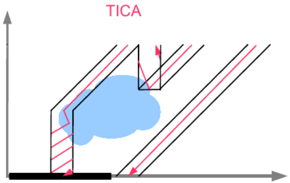
Radiative transfer describes photon interactions with atmosphere.
MonteCarlo modelling of scattering and absorption:



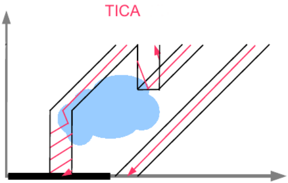
simplify to solve:

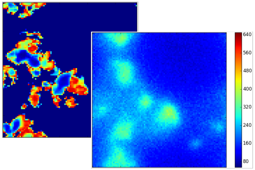
- Plane Parallel approx.
- Independent Column approx.
- Twostream solvers
- diagonal band-matrix (5)

History of 3D RT parametrizations



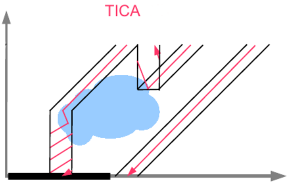
- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)

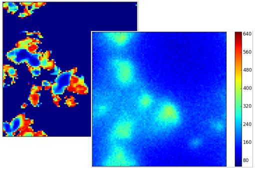




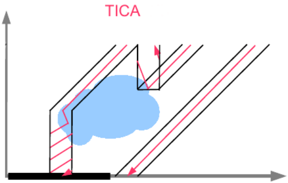
- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)
- Non-local ICA (Marshak 1998)

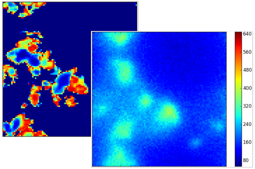
History of 3D RT parametrizations





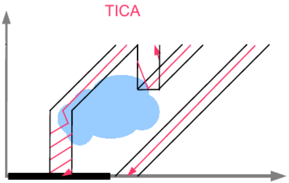
- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)
- Non-local ICA (Marshak 1998)
- displaced shadow regions (Schumann 2002)
- TICA in EULAG (Wapler 2008)
- paNTICA with parameterized kernel size (Wissmeier 2012)

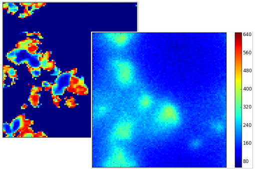




- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)
- Non-local ICA (Marshak 1998)
- displaced shadow regions (Schumann 2002)
- TICA in EULAG (Wapler 2008)
- paNTICA with parameterized kernel size (Wissmeier 2012)
- Ξ TICA implementation in COSMO (Jakub 2013)

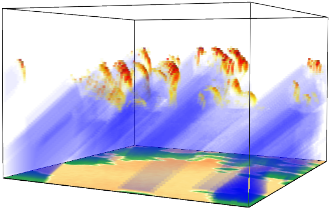
History of 3D RT parametrizations





- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)
- Non-local ICA (Marshak 1998)
- displaced shadow regions (Schumann 2002)
- TICA in EULAG (Wapler 2008)
- paNTICA with parameterized kernel size (Wissmeier 2012)
- Ξ TICA implementation in COSMO (Jakub 2013)
- NCA longwave heating rate corr. (Klinger 2015)
- TenStream 3D finite volume RT (Jakub 2015)

A new concept for a solver – what do we want?

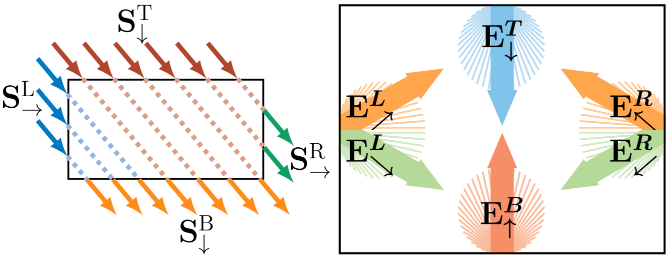


I3RC cloud scene, benchmark heating rate calculation with MYSTIC (MonteCarlo code)

- accurately approximate 3D effects
- has to be several orders of magnitude faster than state of the art 3D solvers
- parallelizable on modern machines

The TenStream solver

Finite Volume formalism:
Discretization of energy transport – spatially and by angle



(a) direct streams (θ=40°)   (b) diffuse streams

Fabian Jakub and Bernhard Mayer, 2015. A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models – The TenStream solver (JQSRT)

Setup equation system for one voxel:

$$\begin{bmatrix} \mathrm{E}^{\mathrm{T}}_{\uparrow} \\ E^{\mathrm{B}}_{\downarrow} \\ E^{\mathrm{L}}_{\swarrow} \\ E^{\mathrm{R}}_{\searrow} \\ E^{\mathrm{L}}_{\nwarrow} \\ E^{\mathrm{R}}_{\nearrow} \\ S^{\mathrm{B}}_{\downarrow} \\ S^{\mathrm{R}}_{\rightarrow} \end{bmatrix} = \begin{bmatrix} \gamma_1 & \gamma_2 & \gamma_3 & \gamma_3 & \gamma_4 & \gamma_4 & \beta_{01} & \beta_{11} \\ \gamma_2 & \gamma_1 & \gamma_4 & \gamma_4 & \gamma_3 & \gamma_3 & \beta_{02} & \beta_{12} \\ \gamma_5 & \gamma_6 & \gamma_7 & \gamma_8 & \gamma_9 & \gamma_{10} & \beta_{03} & \beta_{13} \\ \gamma_5 & \gamma_6 & \gamma_8 & \gamma_7 & \gamma_{10} & \gamma_9 & \beta_{04} & \beta_{14} \\ \gamma_6 & \gamma_5 & \gamma_9 & \gamma_{10} & \gamma_7 & \gamma_8 & \beta_{05} & \beta_{15} \\ \gamma_6 & \gamma_5 & \gamma_{10} & \gamma_9 & \gamma_8 & \gamma_7 & \beta_{06} & \beta_{16} \\ 0 & 0 & 0 & 0 & 0 & 0 & \alpha_{00} & \alpha_{10} \\ 0 & 0 & 0 & 0 & 0 & 0 & \alpha_{01} & \alpha_{11} \end{bmatrix} \begin{bmatrix} \mathrm{E}^{\mathrm{B}}_{\uparrow} \\ E^{\mathrm{T}}_{\downarrow} \\ E^{\mathrm{R}}_{\swarrow} \\ E^{\mathrm{L}}_{\searrow} \\ E^{\mathrm{R}}_{\nwarrow} \\ E^{\mathrm{L}}_{\nearrow} \\ S^{\mathrm{T}}_{\downarrow} \\ S^{\mathrm{L}}_{\rightarrow} \end{bmatrix}$$

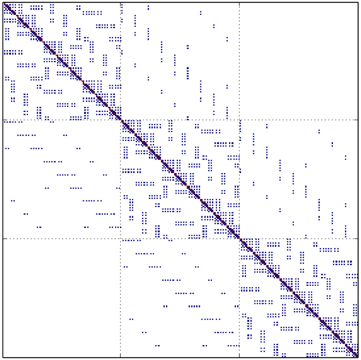
The TenStream solver

Setup equation system for one voxel:

$$
\begin{bmatrix} E^{\mathrm{T}}_{\uparrow} \\ E^{\mathrm{B}}_{\downarrow} \\ E^{\mathrm{L}}_{\swarrow} \\ E^{\mathrm{R}}_{\searrow} \\ E^{\mathrm{L}}_{\nwarrow} \\ E^{\mathrm{R}}_{\nearrow} \\ S^{\mathrm{B}}_{\downarrow} \\ S^{\mathrm{R}}_{\rightarrow} \end{bmatrix}
=
\begin{bmatrix}
\gamma_1 & \gamma_2 & \gamma_3 & \gamma_3 & \gamma_4 & \gamma_4 & \beta_{01} & \beta_{11} \\
\gamma_2 & \gamma_1 & \gamma_4 & \gamma_4 & \gamma_3 & \gamma_3 & \beta_{02} & \beta_{12} \\
\gamma_5 & \gamma_6 & \gamma_7 & \gamma_8 & \gamma_9 & \gamma_{10} & \beta_{03} & \beta_{13} \\
\gamma_5 & \gamma_6 & \gamma_8 & \gamma_7 & \gamma_{10} & \gamma_9 & \beta_{04} & \beta_{14} \\
\gamma_6 & \gamma_5 & \gamma_9 & \gamma_{10} & \gamma_7 & \gamma_8 & \beta_{05} & \beta_{15} \\
\gamma_6 & \gamma_5 & \gamma_{10} & \gamma_9 & \gamma_8 & \gamma_7 & \beta_{06} & \beta_{16} \\
0 & 0 & 0 & 0 & 0 & 0 & \alpha_{00} & \alpha_{10} \\
0 & 0 & 0 & 0 & 0 & 0 & \alpha_{01} & \alpha_{11}
\end{bmatrix}
\begin{bmatrix} E^{\mathrm{B}}_{\uparrow} \\ E^{\mathrm{T}}_{\downarrow} \\ E^{\mathrm{R}}_{\swarrow} \\ E^{\mathrm{L}}_{\searrow} \\ E^{\mathrm{R}}_{\nwarrow} \\ E^{\mathrm{L}}_{\nearrow} \\ S^{\mathrm{T}}_{\downarrow} \\ S^{\mathrm{L}}_{\rightarrow} \end{bmatrix}
$$

Coupling voxels in 3 dimensions. . .

. . . gives huge but sparse matrix.

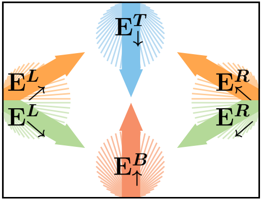


$\Longrightarrow$ solve with PETSc!

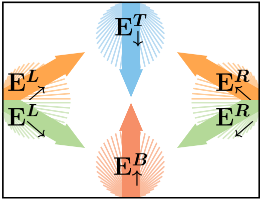
F. Jakubi, B. Mayer, 2015. 3-D radiative transfer in LES - experiences coupling the TenStream solver to the UCLA-LES (GMDD)

Energy transport coefficients

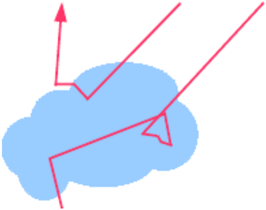
We need to determine the energy transport from one stream to another:



We need to determine the energy transport from one stream to another:

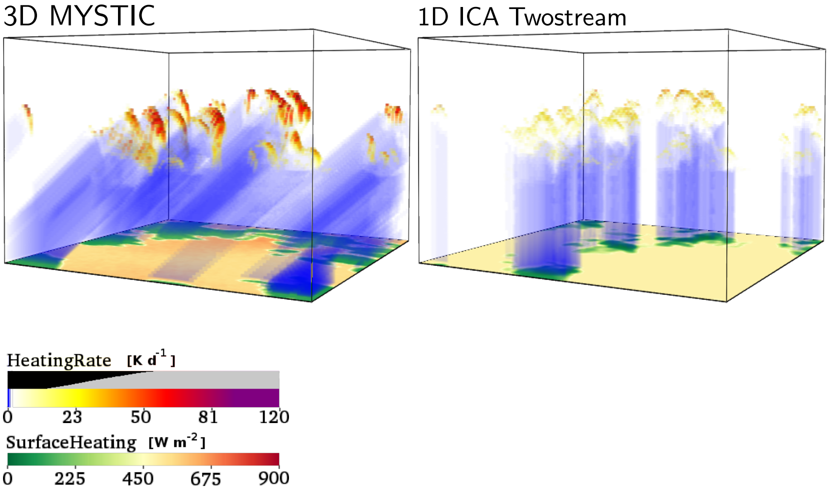


$\rightarrow$ solve radiative transfer equation with MonteCarlo method



... and put them into LookUpTable

Comparison to MYSTIC

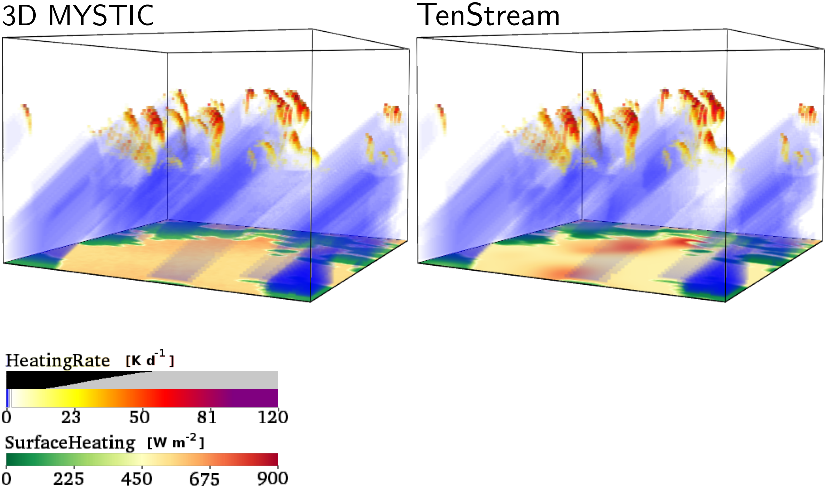


Jakub, F. and Mayer, B. (2016) A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models – The TenStream solver (JQSRT) https://doi.org/10.1016/j.jqsrt.2015.05.003

Jakub, F. and Mayer, B. (2016) 3-D radiative transfer in large-eddy simulations – experiences coupling the TenStream solver to the UCLA-LES (GMD) https://doi.org/10.5194/gmd-9-1413-2016

Computations done with libRadtran (Library for Radiative Transfer, libradtran.org)

Comparison to MYSTIC

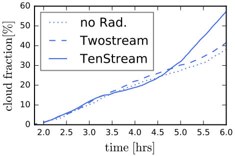


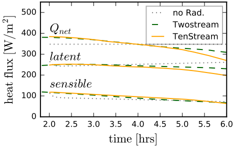
Jakub, F. and Mayer, B. (2016) A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models – The TenStream solver (JQSRT) https://doi.org/10.1016/j.jqsrt.2015.05.003

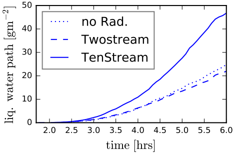
Jakub, F. and Mayer, B. (2016) 3-D radiative transfer in large-eddy simulations – experiences coupling the TenStream solver to the UCLA-LES (GMD) https://doi.org/10.5194/gmd-9-1413-2016

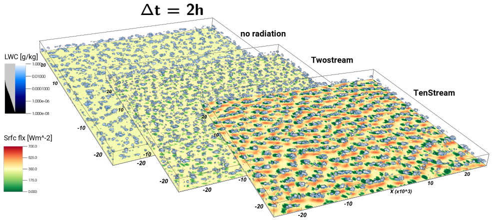
Computations done with libRadtran (Library for Radiative Transfer, libradtran.org)

Shallow cumulus experiments









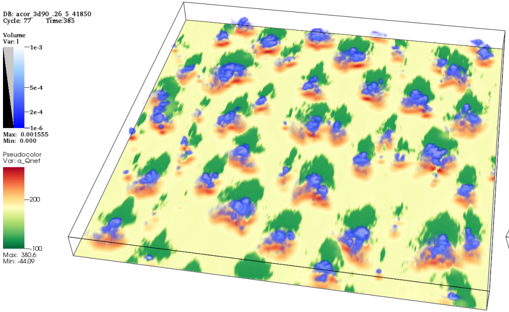
wind $\mathbf{u = 0\,m/s,\;\; sza\theta = 60^\circ}$

- 3D radiation produces larger, higher and thicker clouds
- const. influx of moist air increases cloud lifetime (2x)
- more efficient moisture flux into the cloud layer

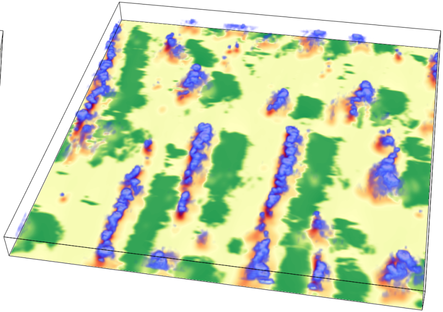
Jakub, F. and Mayer, B. (2017) The role of 1-D and 3-D radiative heating in the organization of shallow cumulus convection and the formation of cloud streets (ACP) https://doi.org/10.5194/acp-17-13317-2017

Convective Organization in Streets

Sun in the South

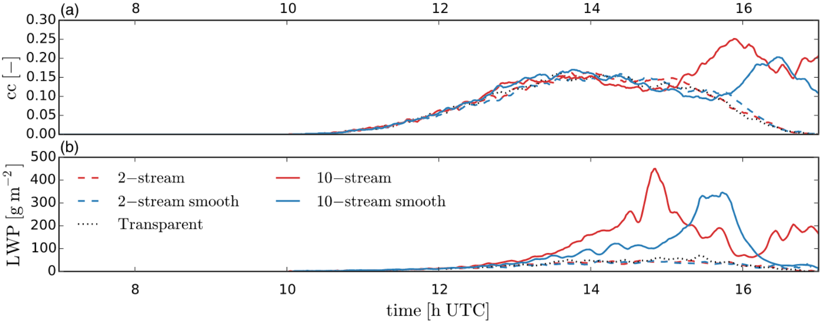


Sun in the West



F. Jakub, 2017. The Role of 1D and 3D Radiative Heating on the Organization of Shallow Cumulus Convection and the Formation of Cloud Streets

Shallow cumulus during a diurnal cycle



Internship of Menno Veerman

- DALES shallow convection simulations with a diurnal cycle
- **organization** with secondary circulations vs. popcorn convection
- Interactions between **radiation**, **clouds** and the **surface** lead to considerable changes in cloud size distribution and updraft efficiency

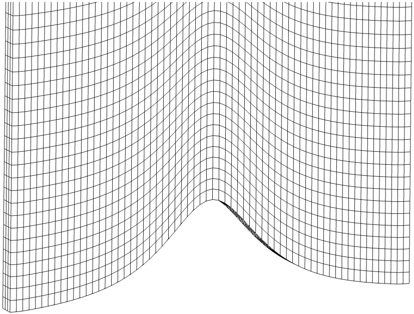
Veerman, M. A. et al (2020). Three-dimensional radiative effects by shallow cumulus clouds on dynamic heterogeneities over a vegetated surface. (JAMES) https://doi.org/10.1029/2019MS001990

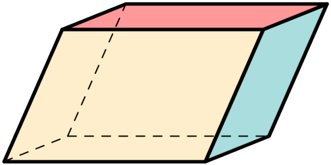
WRF LES with mountains

stationary cumulus above Stellihorn (Wallis) (CC wikipedia)

WRF LES with mountains

Orography realized with ground following σ-coordinates:

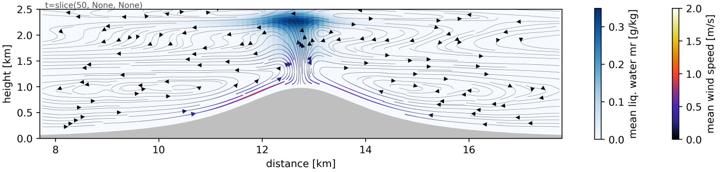




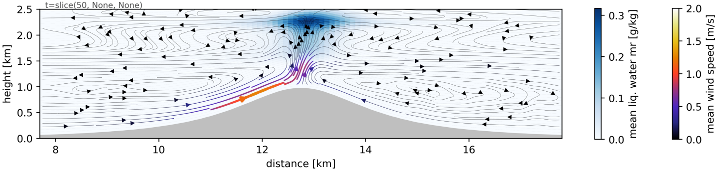
Masterthesis of H. Böttcher

- solve propagation of radiation through distorted meshes, by projecting “outgoing“ faces onto “incoming“ faces along sundirection and integrating lambert-beer extinction through partial volumes
- approximation: parallelepiped – opposite faces are parallel

WRF LES with mountains



1D

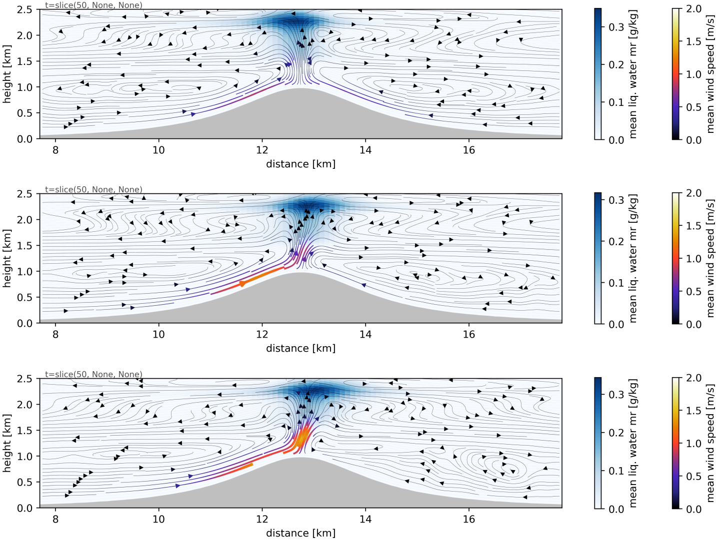


1D

slope

corrected

WRF LES with mountains

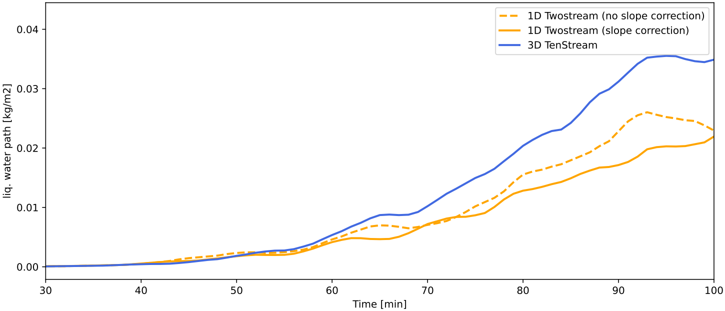


1D

1D slope corrected

3D TenStream

WRF LES with mountains



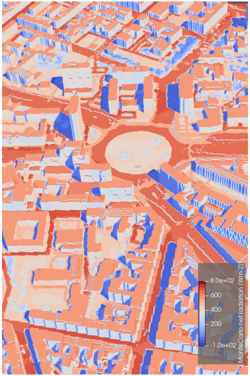
continued illumination of mountain top leads to

- stronger updrafts
- enhanced cloud development
- earlier onset of rain

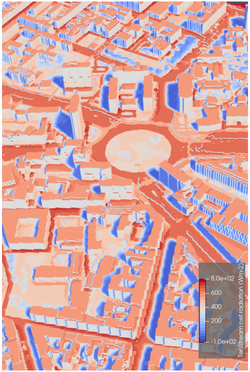
"Urban Climate Under Change" [UC]2 (MOSAIK-2) project

$\longrightarrow$ extended TenStream to support voxel boundaries

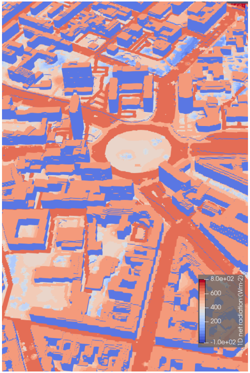
Net surface flux (lw+sw):



MonteCarlo

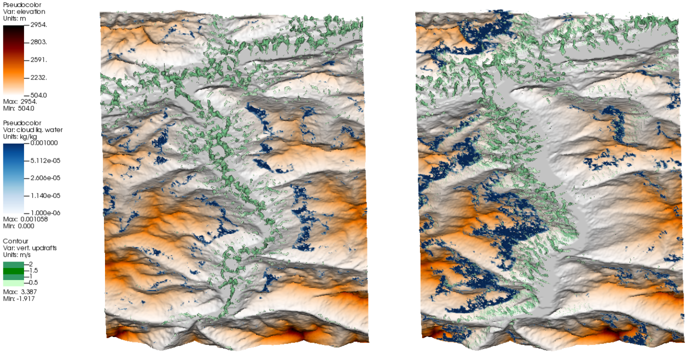


TenStream



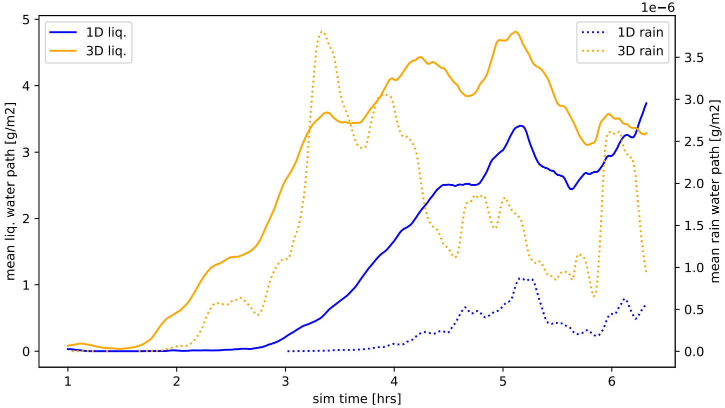
2-stream

PALM LES Zillertal



Idealized PALM-LES setup

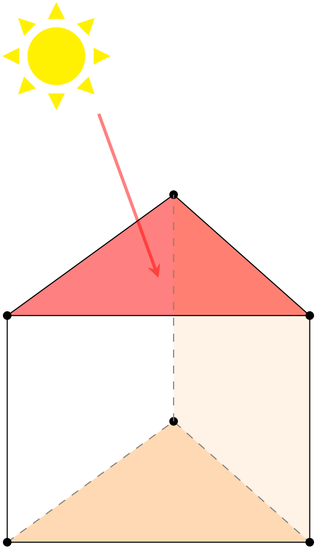
- $\Delta x = 50\mathrm{m}$
- June, morning to afternoon
- no mesoscale forcing
- homogeneous surface type



continued illumination of mountain top leads to

- stronger updrafts
- enhanced cloud development
- earlier onset of rain

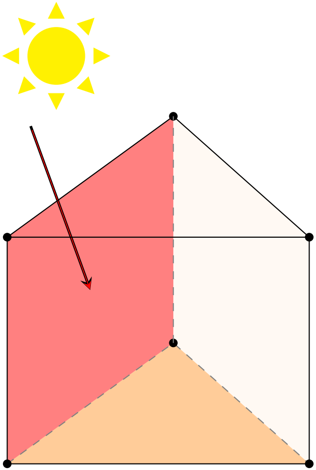
Propagation of Radiation in Wedges



3D propagation of radiation through wedges needs to account for:

- transport between each face
- including **absorption**
- and **multiple scattering**

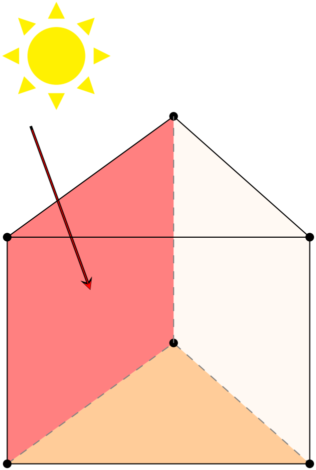
Propagation of Radiation in Wedges



3D propagation of radiation through wedges needs to account for:

- transport between each face
- including **absorption**
- and **multiple scattering**

Propagation of Radiation in Wedges



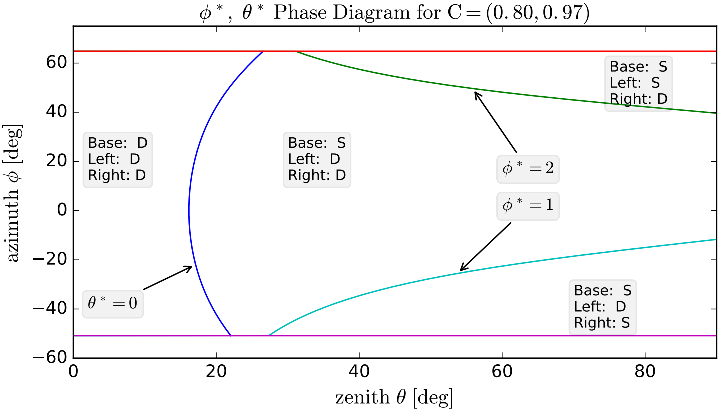
3D propagation of radiation through wedges needs to account for:

- transport between each face
- including **absorption**
- and **multiple scattering**

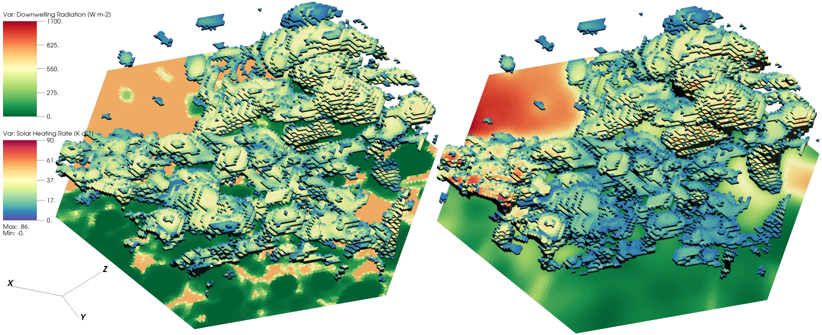
then

. . . **couple voxels** and **solve**

Source/Destination Phase Diagram for an ICON Wedge Element



1D and 3D Radiation in ICON

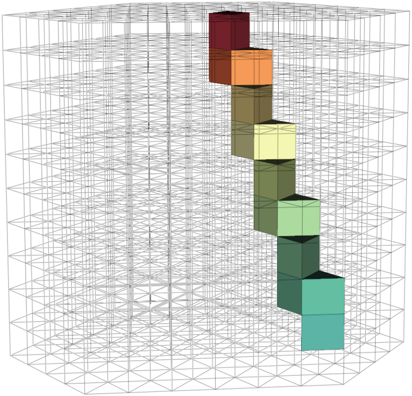


1D Twostream

3D TenStream
(8-streams actually)

Work on 3D Radiative transfer in ICON

Implementation of 3D-Radiation in ICON-LEM is available, however if there was more time . . .



. . . we'd apply lessons learned from quad meshes:

- reorder equations along sun direction to optimize iterative solvers
- handle terrain following coordinates to allow simulations with elevation differences

Recent developments

Recent performance improvements

- incomplete solves

  R. Maier et al, 2024. A dynamic approach to three-dimensional radiative transfer in subkilometer-scale numerical weather prediction models: the dynamic TenStream solver (GMD)

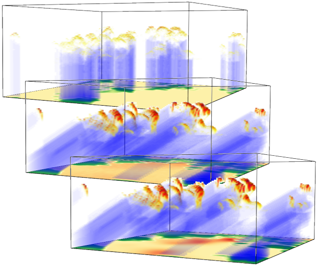
- new spectral integration schemes
  - "ecckd" R. Hogan and M. Matricardi, 2022. A Tool for Generating Fast k-Distribution Gas-Optics Models for Weather and Climate Applications (JAMES)
  - "repint" M.Mourgues and C.Emde and B.Mayer, 2023. Optimized Wavelength Sampling for Thermal Radiative Transfer in Numerical Weather Prediction Models (MDPI)

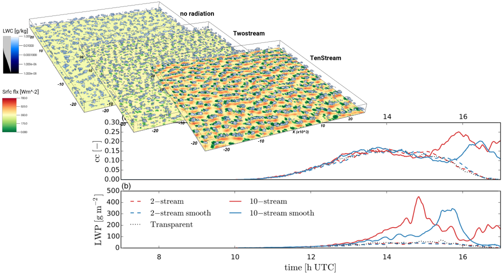
...provide 3D radiation at approx. the cost of RRTMG 1D RT

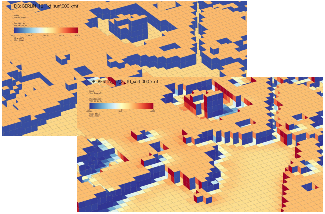
Current efforts @ LMU, Univ. Munich

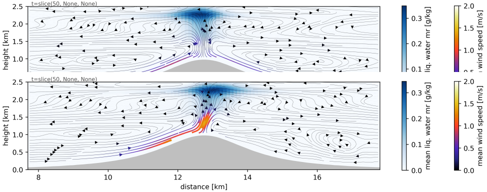
- incomplete solves (R.Maier, PhD)
- unify grid scale transport + sub-grid effects (M.Manev, PhD)

Thank you!









M.Mourgues and C.Emde and B.Mayer, 2023. Optimized Wavelength Sampling for Thermal Radiative Transfer in Numerical Weather Prediction Models (MDPI)
R. Maier et al,2024. A dynamic approach to three-dimensional radiative transfer in subkilometer-scale numerical weather prediction models: the dynamic TenStream solver (GMD)
Veerman, M. A. et al (2020). Three-dimensional radiative effects by shallow cumulus clouds on dynamic heterogeneities over a vegetated surface (JAMES)
F. Jakub, 2017. The Role of 1D and 3D Radiative Heating on the Organization of Shallow Cumulus Convection and the Formation of Cloud Streets (ACP)
F. Jakub, 2016. On the impact of three dimensional radiative transfer on cloud evolution
F.Jakub and B.Mayer, 2016. 3-D radiative transfer in large-eddy simulations – experiences coupling the TenStream solver to the UCLA–LES, (GMD 2016)
F.Jakub and B.Mayer, 2016. A three-dimensional parallel radiative transfer model for atmospheric heating rates for use in cloud resolving models – The TenStream solver (JQSRT)