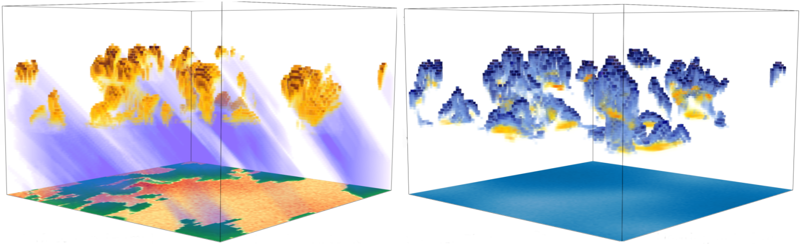
3D Radiative Transfer in Cloud Resolving Models

Fabian Jakub, Carolin Klinger

LMU - Meteorological Institute Munich



November 16, 2015

Does 3D Radiative Transfer impact cloud evolution?

Earlier studies suggest radiation may affect

- cloud evolution and lifetime
- microphysical processes (condensation, nucleation)
- precipitation onset/amount
- convective organization

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Can we model radiative transfer in the atmosphere?

$HD(CP)^2$ project (www.hdcp2.eu)

HD(CP)²

High definition clouds and precipitation
for advancing climate prediction

- run hindcasts over Central Europe
- 100m horizontal resolution
- grids consisting of 10.000 x 15.000 x 300 voxels
- first develop a model capable of running it (ICON)
- . . . with the goal to develop improved parameterizations for weather and climate predictions

History of Radiative Transfer

Radiative Transfer theory well established

- radiative transfer equation (1960 Chandrasekhar)

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

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- sophisticated 3D models since the 90's (e.g. MonteCarlo)

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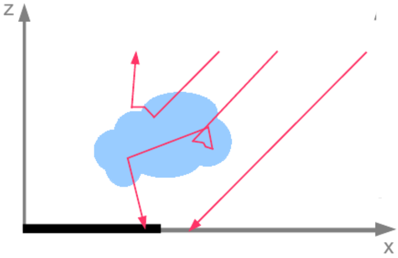
- surprisingly well working 1D approximations
- sophisticated 3D models since the 90's (e.g. MonteCarlo)
- . . . but orders of magnitude too slow to run in atmospheric models

Approximations for Radiative Transfer

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



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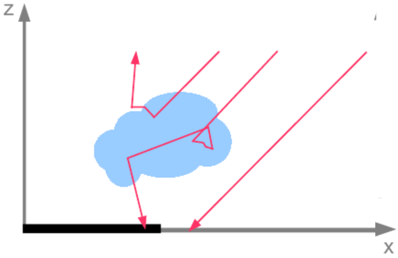

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- Plane Parallel approx.
- Independent Column approx.

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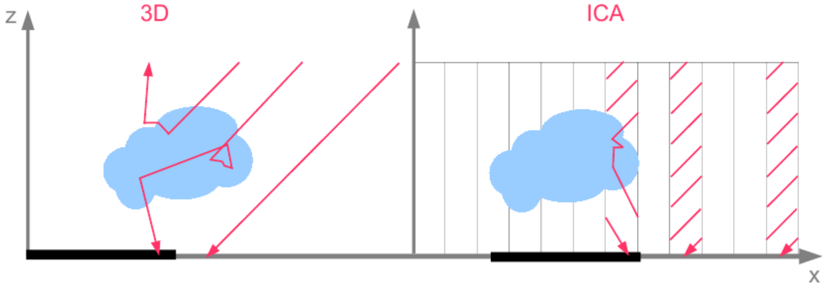
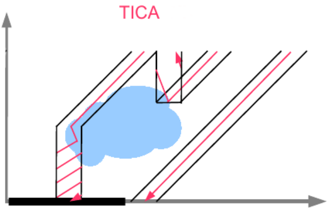


simplify to solve:

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

A walk through the ages

3D parameterizations – a tradition at MIM:



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

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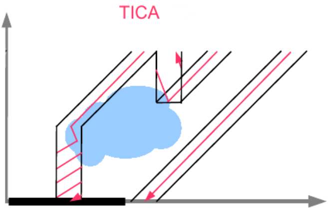

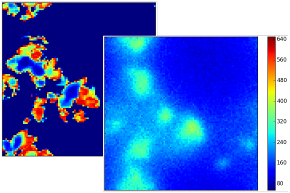

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- Non-local ICA (Marshak 1998)

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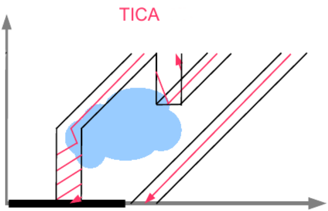
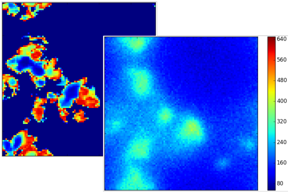




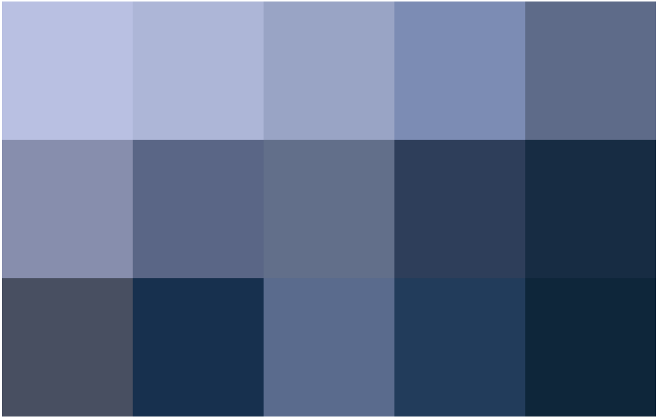
- Tilted-ICA (Gabriel and Evans 1996, Varnai 1999)
- Non-local ICA (Marshak 1998)
- displaced shadow regions (Schumann 2002)
- TICA in EULAG (Wapler 2008)
- NICA with automatic kernel size (Wissmeier 2012)

Why care for 3D radiation now? – a matter of resolution

Complex cloud radiation interaction

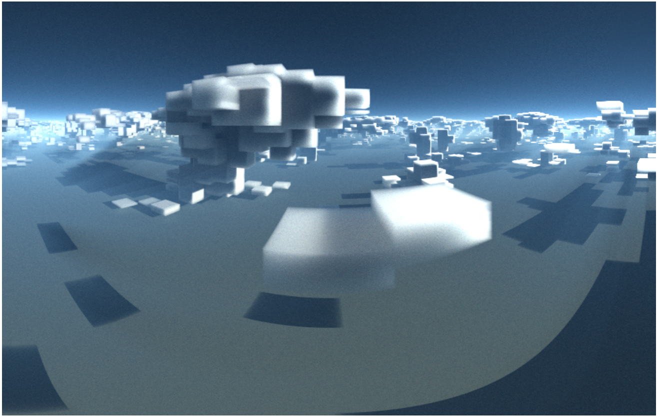
Why care for 3D radiation now? – a matter of resolution

Global models



Why care for 3D radiation now? – a matter of resolution

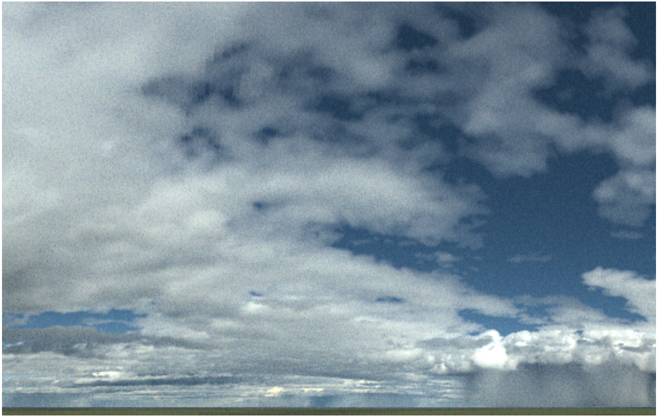
Weather models today



Visualization done with libRadtran.org/**MYSTIC** (Montecarlo code for the phYSically correct Tracing of photons In Cloudy atmospheres) Mayer, B., 2009. Radiative transfer in the cloudy atmosphere (EPJ Web of Conferences)

Why care for 3D radiation now? – a matter of resolution

Next-gen models



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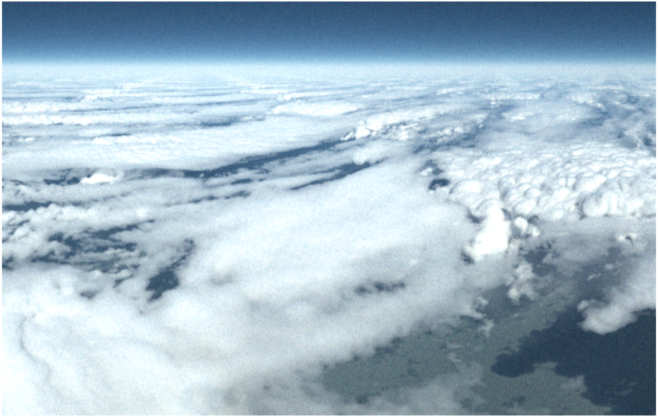

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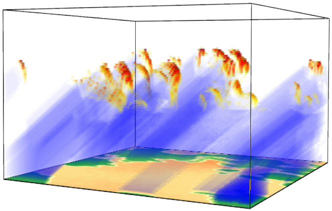
The Tenstream solver

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

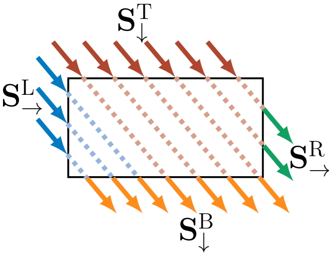


I3RC cloud scene, benchmark heating rate calculation with MYSTIC (MonteCarlo code)

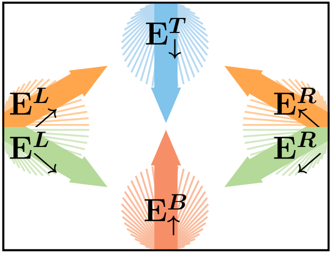
- accurately approximate 3D effects
- has to be several orders of magnitude faster than state of the art 3D solvers
- parallelizable on modern machines

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)

The TenStream solver

Setup equation system for one voxel:

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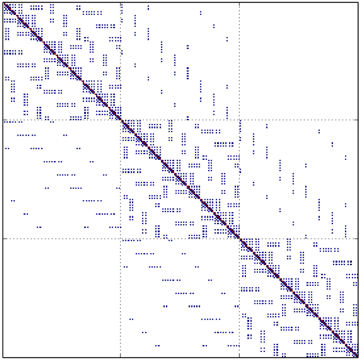
$$

Coupling voxels in 3 dimensions...

...gives huge but sparse matrix.

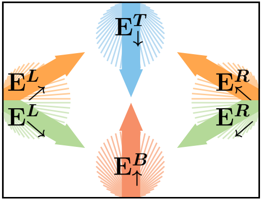


$\implies$ solve with PETSc!

Energy transport coefficients

We need to determine the energy transport

from one stream to another:



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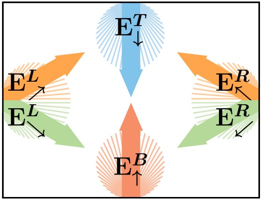
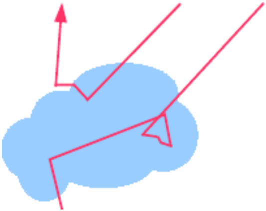


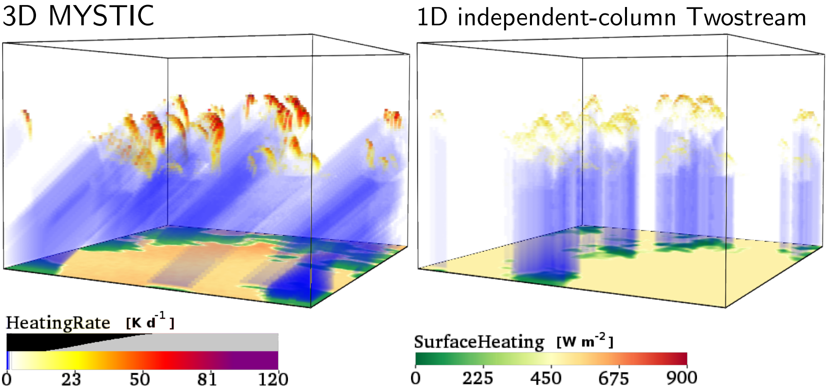
$\rightarrow$ solve radiative transfer equation with

MonteCarlo method



. . . and put them into LookUpTable

Does it work?



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

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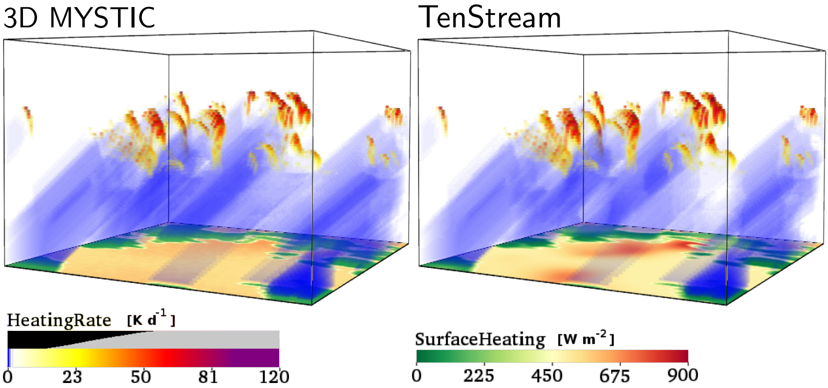

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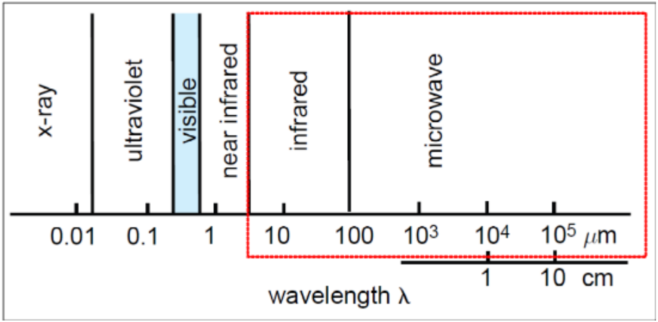
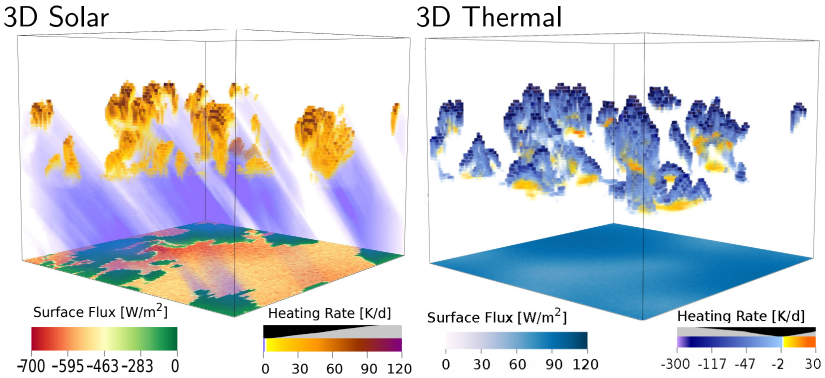
Thermal Radiative Transfer



Thermal spectral range (Wallace and Hobbs 2006, p.114).

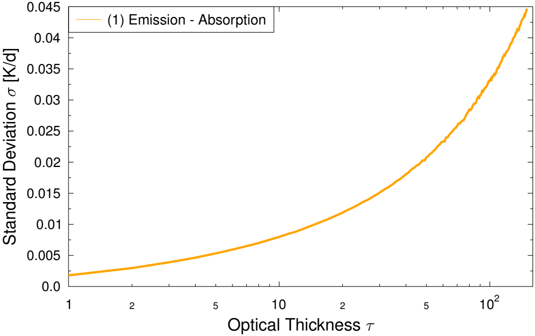
3D Solar vs. Thermal Radiative Transfer



Monte Carlo Variance Reduction Techniques

Emission–Absorption

$$\frac{dT}{dt} = -\frac{1}{\rho\, c_p}(\dot{q}_{em} - \dot{q}_{abs})$$



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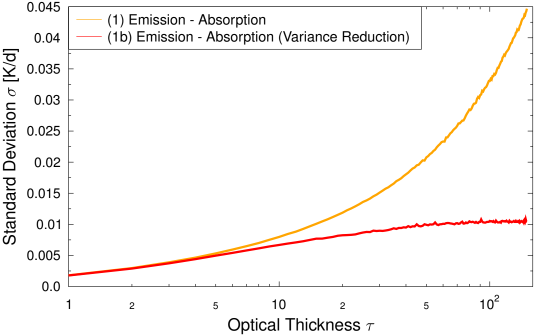
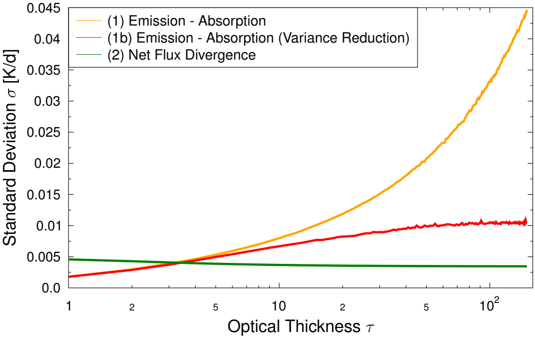


Monte Carlo Variance Reduction Techniques

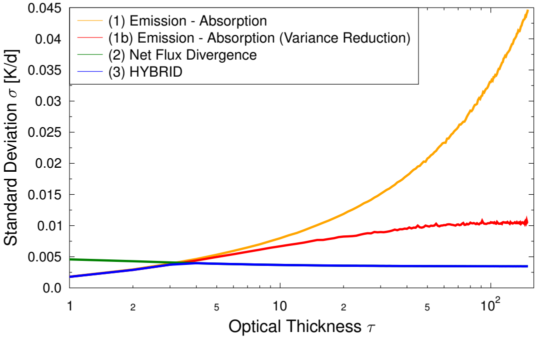
Net Flux Divergence

$$\frac{dT}{dt} = -\frac{1}{\rho\, c_p} \nabla \vec{E}_{\mathrm{net}}$$

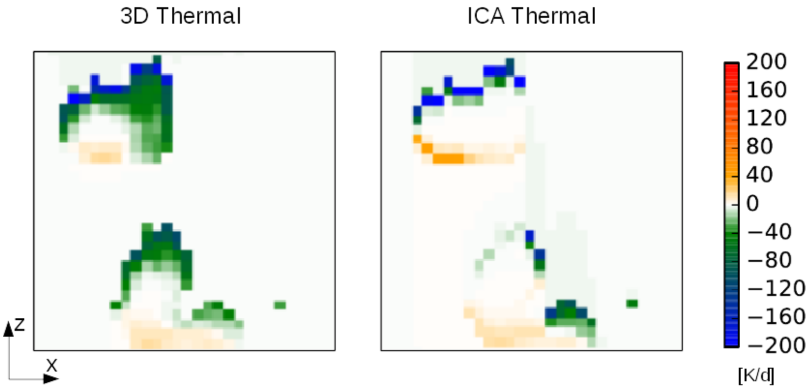


Monte Carlo Variance Reduction Techniques

Combining Emission–Absorption and Net Flux Divergence to HYBRID

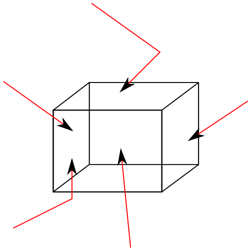


3D vs. 1D Thermal Radiative Transfer



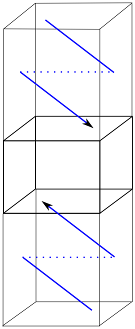
Neighboring Column Approximation NCA

MYSTIC



NCA

ICA



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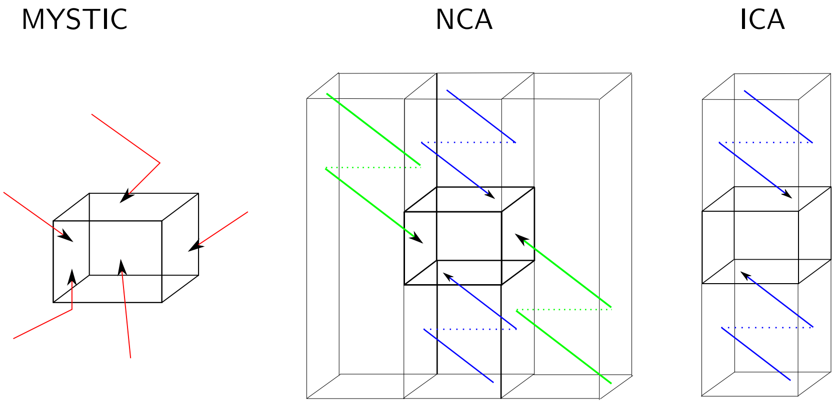

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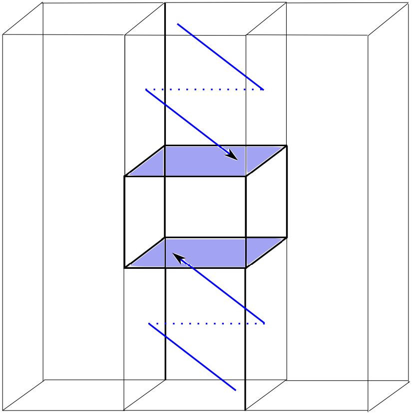

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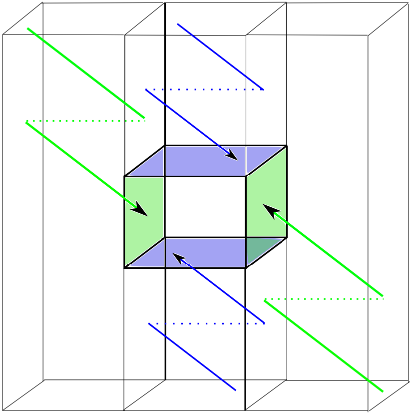

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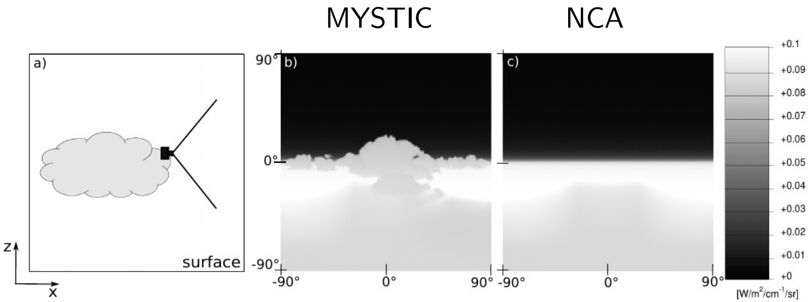


Neighboring Column Approximation NCA

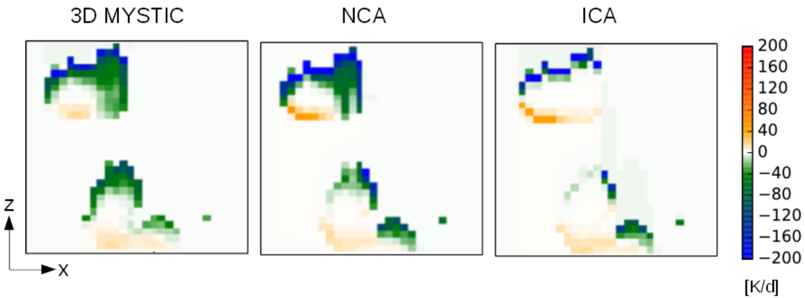
$$L_{\mathrm{abs,bc1}} = \frac{1}{\Delta z}\, B_{\mathrm{i-1}}\, (c-b) \tag{3.44}$$

$$L_{\mathrm{abs,bc2}} = -\frac{1}{\Delta z}\, (L_{\mathrm{s1}} - B_{\mathrm{i-1}})\, \frac{\cos\theta}{\beta_{\mathrm{abs,i-1}}} \left[\exp\left(-\beta_{\mathrm{abs,i-1}} \frac{c}{\cos\theta}\right) - \exp\left(-\beta_{\mathrm{abs,i-1}} \frac{b}{\cos\theta}\right)\right] \tag{3.45}$$

$$\begin{aligned} L_{\mathrm{abs,bc3}} \quad & = -\tfrac{1}{\Delta z}\, (L_{\mathrm{s1}} - B_{\mathrm{i-1}})\, \tfrac{\cos\theta}{\beta_{\mathrm{abs,i}} - \beta_{\mathrm{abs,i-1}}} \\ & \exp\left(-\beta_{\mathrm{abs,i}} \tfrac{\Delta z}{\cos\theta}\right) \left[\exp\left(\tfrac{(\beta_{\mathrm{abs,i}} - \beta_{\mathrm{abs,i-1}})\,(c-b)}{\cos\theta}\right)\right] \end{aligned} \tag{3.46}$$

$$L_{\mathrm{abs,bc4}} = -\frac{1}{\Delta z}\, B_{\mathrm{i-1}}\, \frac{\cos\theta}{\beta_{\mathrm{abs,i}}}\, \exp\left(-\beta_{\mathrm{abs,i}} \frac{\Delta z}{\cos\theta}\right) \left[\exp\left(\frac{c\,\beta_{\mathrm{abs,i}}}{\cos\theta}\right) - \exp\left(\frac{b\,\beta_{\mathrm{abs,i}}}{\cos\theta}\right)\right] \tag{3.47}$$

NCA vs. 1D - NCA vs. 3D MYSTIC



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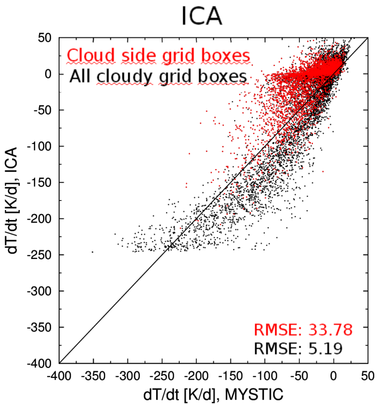
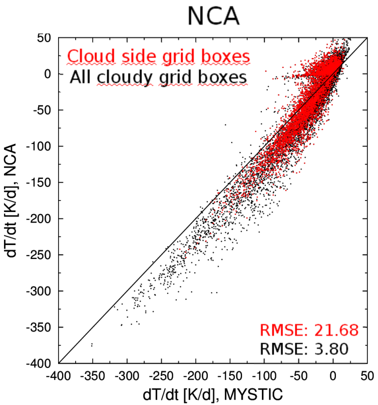




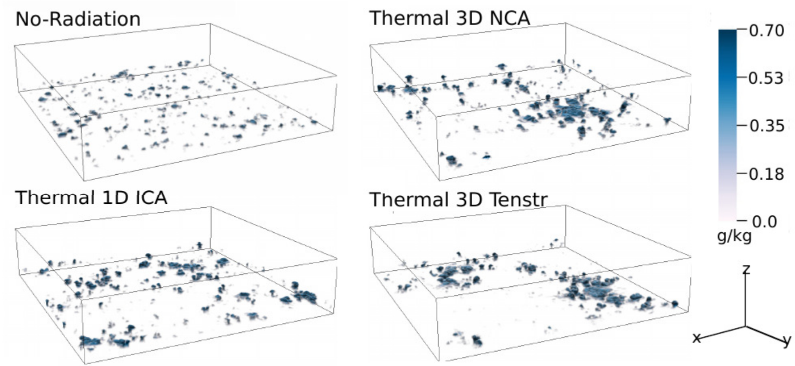
Couple Paramterizations to Atmospheric Model

TenStream solver and NCA coupled to the UCLA-LES

- use LES to model atmospheric flow with resolutions from 10 m to 1 km
- consider dynamics, turbulence, microphysics and radiation
- TenStream solver increases total model runtime by factor 3-5
- NCA only factor 1.5-2 more expensive

Cloud Evolution With 3D Thermal Radiation

Shallow Cumulus Cloud Field



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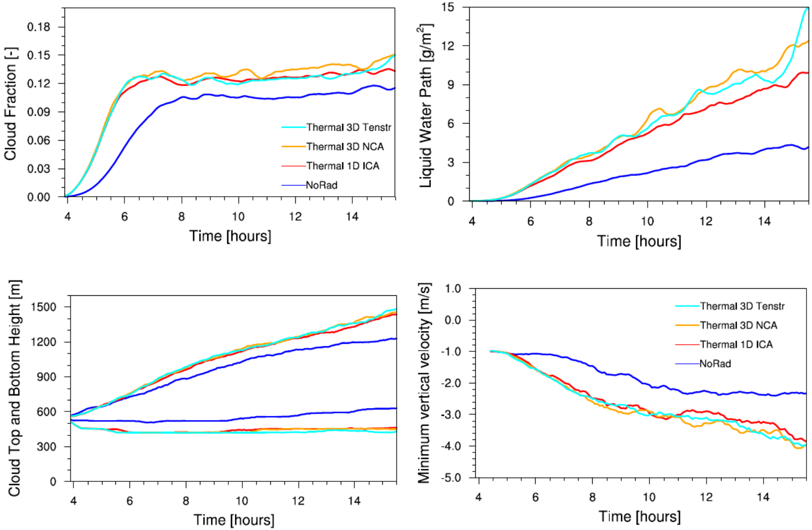
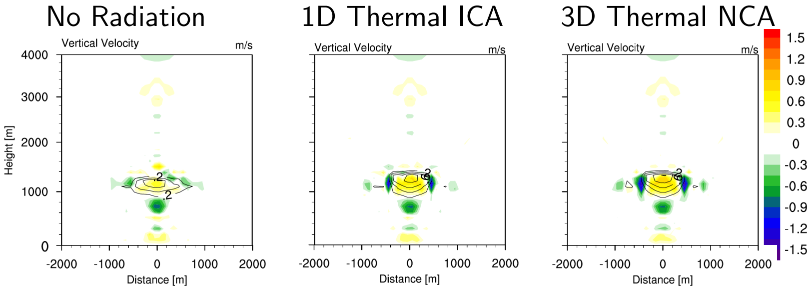


Cloud Evolution With 3D Thermal Radiation

Single Cloud



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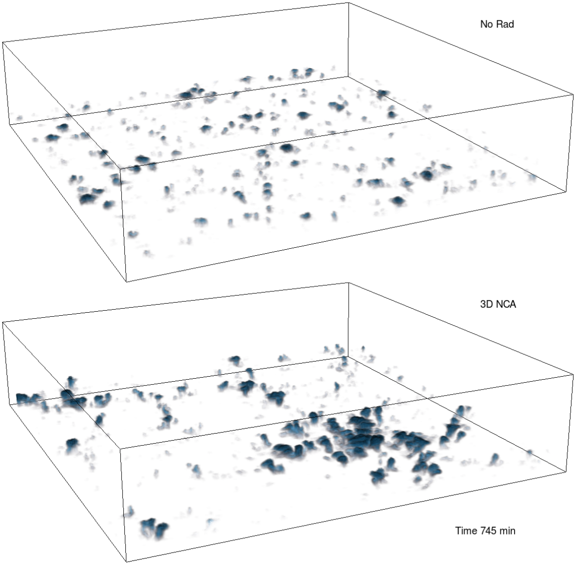
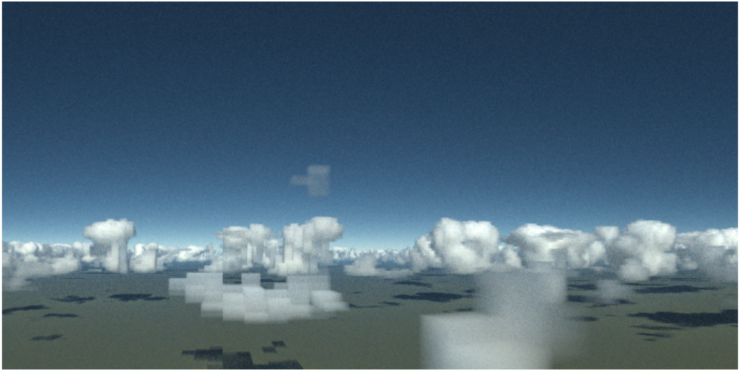


Flying through a Cloud Field



Current state and a glimpse at whats to come..

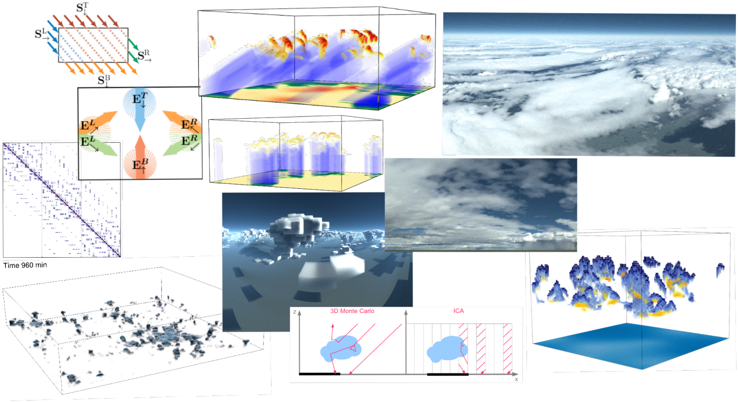
Conclusions

- Development of 2 parallel solvers
- Implemented in UCLA-LES
- Unprecedented large and extensive simulations

Outlook

- Further investigation of simulations (cloud organization)
- RCE simulations
- Get ready for large scale computations in ICON – $\mathrm{HD(CP)}^2$-Project
- Systematic analysis of 3D effects and impact on large scale flow – $W2W$-Project

Thank you!



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